Study On The Phase Transition Characteristics Of Vanadium Dioxide Film With A Single Laser Pulse Irradiated On It

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Abstract. VO₂, used as a thermochromatic material, and its crystalline structure may undergo a reversible phase transition between semiconductor and metal under certain temperature. The reversible phase transition characteristic was introduced and the reversible phase transition mechanism was studied. According to the laser disturbance and photo-electricity detector damage mechanism, the anti-laser interference based on VO₂ film was studied. The calculation and analysis were processed. The results showed that, when a single laser pulse was irradiated in a detector protected by VO₂ film, the VO₂ film will achieve phase transition before the laser disturbance and damage the detector. The VO₂ thin film can be used to prevent laser interference.

1. Introduction
In order to cope with the increasingly diffused infrared guided missile, western developed countries have developed many types of directional infrared jamming system. Infrared seeker is weak signal amplifier, which is very sensitive and it is the object to be attacked and interference[1]. An interference method is that a strong laser was used to irradiate infrared seeker. The infrared detector of the seeker was interfered, so that it would not work properly[2]. The laser directed jamming system starts to develop to the high-efficiency damage direction based on the laser-based fiber tactical laser weapon and pulsed laser weapon[3]. Laser can produce three kinds of interference effects, which are angle deception, soft killing and hard damage. The interference effect is related to laser power, distance and atmospheric conditions.

Infrared detector is a weak light detector, which means that laser irradiation can interfere the infrared detector easily. The infrared detector extremely easily lose its detection ability, thus the whole photo-voltaic system cannot work normally, even damage[4].

In the United States and some developed countries, the infrared directional jamming system has been equipped with troops. Among them, the United States developed four more typical infrared directional jamming laser systems, such as AN/aaq-24 (V) DIRCM system. The United States has also equipped with a variety of vehicle-mounted, airborne and hand-held laser blinding weapons which can blinding human eyes and light detectors at a distance of 1km[5]. In addition, Russia, Germany, France, Britain, Israel and other countries also have developed a dozen similar equipment.

Laser protective material have many types. In general, we divide it into linear materials, nonlinear materials and phase transition materials[6]. To deal with the threat that the laser interfering...
photoelectric detector, it is necessary to develop a laser protection materials which has enough wide bandwidth, low enough protection the output of the threshold, the weak radiation has a high linear transmittance and the response time of nanosecond[7].

One promising protective material is vanadium dioxide[8]. The vanadium dioxide has semiconductor - metal phase transition properties. In the semiconductor state, the material has high transmission characteristics to the infrared radiation, while in the metal state, the material is highly reflective characteristics, which makes it have the potential to be used as intelligent optical switch.

The phase transition temperature of vanadium dioxide is closest to room temperature. The phase transition of vanadium dioxide has characteristic of high speed phase transition, reversible and wide band width, and it has a wide application prospect in anti-infrared directional energy. Using vanadium oxide film to resist laser directed interference, it is better to complete phase transition when the first disturbance pulse arrives, thus protecting the detector[9].

2. The phase transition properties of vanadium dioxide.

Vanadium oxide is a kind of variable valence oxide, which has three valence (V_2O_3), four (VO_2) and five valence (V_5O_8) and other forms of vanadium oxides. When the ambient temperature changes, reversible transformation of vanadium oxide will occur between the semiconductor and metal-insulator, and the resistivity and infrared radiation transmittance will be mutate. The phase transition temperature of vanadium dioxide is 68℃. This phase transition characteristic can be used to counter the infrared directional jamming system. Current Directional Infrared Counter Measures (DIRCM) system mainly work in mid-infrared band, if the vanadium oxide thin films was used to protect infrared detector, it is need to satisfy the following two conditions: first, before the phase transition, film should have high transmittance so it will not affect the infrared detector to receive signals; second, after the phase transition, the low transmittance of the film makes that the Directional Infrared Counter Measures (DIRCM) system can’t damage the detector.

![Fig. 1 Thin film high and low temperature transmission spectrum curve.](image)

3. The basic analysis of vanadium oxide film against Directional Infrared Counter Measures.

Only when the corresponding energy threshold is reached, can the laser cause the seeker's infrared sensor interference or damage. The energy contained in a single laser pulse of Directional infrared Counter Measures system is very high. A pulse of DIRCM can cause interference to the infrared detector, therefore, the phase transition of vanadium oxide thin films should be completed when the first attack incident pulse arrive.

Laser damage mechanism of all kinds of photoelectric was studied in many countries, a consistent conclusion is that, under the present laser technique, laser interference a photoelectric detector is basically based on heat effect. There is an energy density threshold when a laser was used to interfere or destroy the photoelectric detector. When the laser energy is higher than this threshold, the detector will be disturbed or damaged. Different detectors have different interference or damage thresholds[10]. When the high pulsed power laser irradiates on a detector and cause it reach saturation...
state, it will cause interference. When a vanadium dioxide film was used to protect a detector, the phase transition of the film must be completed before the laser has interfered he detector.

In the phase transition process, the electrical and optical properties of vanadium dioxide film will mutate. This optical band mutation character can be used to protect the detector from laser interference. VO2 thin film to protect the detector need to meet certain conditions. Besides the energy, phase transition response time and recovery time are also the keys to its application in the field of laser protection. So the following three conditions need to be satisfied:

1. A single pulse cause phase transition; A high power laser pulse is likely to interfere a detector. So the energy of the first laser pulse can cause the phase transition of the vanadium dioxide film is needed.
2. Film phase transition speed must be fast; In order to avoid losing the target in the process of high-speed flight, the working frame of the detector must reach a certain speed. The phase change speed of the film is higher than the frame rate. If the working frame rate of a imaging detector is 100 frames per second, the phase transition speed of vanadium dioxide film should be less than 10 milliseconds.
3. When the interference disappears, the recovery time is fast; When the laser interference pulse disappears, vanadium dioxide film needs to be quickly restored to the working state to ensure that the detector works normally.

4. **Vanadium dioxide film phase transition energy threshold under a single laser pulse**

From the energy point of view, when the laser irradiates to the vanadium dioxide film, part of the laser passes through the film, and the other part is absorbed by the film. When the film absorbs energy, the temperature rises. When the film temperature rises high to the phase transition temperature, the film phase transition will happen. The energy needed to rise the film to the phase transition temperature is:

\[
E_{th} = \rho_{VO2}d_{VO2}C_{VO2}(T_p - T_0)
\]

In the formula, \(\rho_{VO2}\) is the film thickness, \(d_{VO2}\) is the film thickness, \(C_{VO2}\) is the heat capacity of the film, \(T_p\) is the phase transition temperature, and \(T_0\) is the ambient temperature.

When a laser beam its the energy is \(E_0\) irradiated on the film, the energy absorbed by the film unit area is:

\[
E_{ab} = E_0 \left(1 - e^{-\alpha_{VO2}(\lambda)d}\right)
\]

\(\alpha_{VO2}(\lambda)\) is the absorption coefficient of the film.

\[
\alpha_{VO2}(\lambda) = \frac{4\pi k_{VO2}(\lambda)}{\lambda}
\]

\(k_{VO2}(\lambda)\) is the extinction coefficient of the film.

To make the phase transition happens on the film, the energy density of the incident laser needs to be greater than the threshold energy of the phase transition.

\[
E_{ab} > E_{th}
\]

Therefore, the energy density of the incident laser needs to meet the following conditions:

\[
E_0 > \frac{\rho d C_T (T_p - T_0)}{1 - \exp\left(-\frac{4\pi k(\lambda)d}{\lambda}\right)}
\]

The relationship between the temperature rise which a single laser pulse led to and the energy absorbed per area is:

\[
T = \frac{E_0 \left[1 - \exp\left(-\frac{4\pi k(\lambda)d}{\lambda}\right)\right]}{\rho_{VO2}d_{VO2}C_{VO2}} + T_0
\]

Vanadium dioxide film was prepared on sapphire substrate by magnetron sputtering method. The basic parameters of the film were as follows:

d=452 nm, VO2 thin film density \(\rho=4.269 \text{ g/cm}^3\), heat capacity \(CT = 1.08 \times 10^2 \text{ J/(K·g)}\), the initial environmental temperature is and room temperature \(T_0 = 20 \text{ °C}\), temperature phase transition temperature is 65 °C. Purely in terms of film, it’s very thin. Very weak energy can make the vanadium oxide thin film phase transition. In fact, the film is always in a variety of plating substrate, the rise of temperature of the basal largely represents the rise of temperature of the film. The base density of
Al2O3 is 3970 (kg/m³) and the thickness is 400(m). If the substrate is to rise to the film phase transition temperature, the unit energy of the incident is required is

$$E_{Al2O3} = \rho_{Al2O3}d_{Al2O3}C_{Al2O3}(T_p - T_0)$$  \tag{7}

In the formula, $\rho_{Al2O3}$ is the base density, $d_{Al2O3}$ is the base thickness, $C_{Al2O3}$ is the heat capacity of the base.

The relationship between substrate temperature rise and incident laser energy is as follows:

$$T = \frac{E_0[1 - \exp\left\{-\frac{2\pi k_{Al2O3}\lambda d}{\lambda}\right\}]}{\rho_{Al2O3}d_{Al2O3}C_{Al2O3}} + T_0$$  \tag{8}

In the formula, $\rho_{Al2O3}$ is the base density, $d_{Al2O3}$ is the base thickness, $C_{VO2}$ is the heat capacity of the base, $T_p$ is the phase change temperature, and $T_0$ is the ambient temperature.

VO2 thin films on sapphire substrate was irradiated by the laser, the initial environmental temperature is 20 ℃ and room temperature $T_0=20$ ℃. Different energy density are obtained by ANSYS finite element analysis software under the action of nanosecond laser temperature rise of the single pulse of VO2 thin film is shown in figure 2. It can be seen from the figure that when the incident laser wavelength illuminates $E_0$ greater than 30 mJ/cm², the single pulse laser can make the film change phase. The energy density of the single pulse incident laser must reach 30mJ/cm². With the increase of pulse laser energy density, the single pulse temperature rise of VO2 films also changes.

![Fig. 2 single pulse temperature rise of VO2 film with different incident laser energy density.](image)

As can be seen from the figure, a laser pulse irradiated vanadium dioxide film coated in the sapphire base, if the single pulse energy density reaches 30mJ/cm², it can make the VO2 film phase transition.

5. The phase transition speed of vanadium dioxide

To prevent the laser from interfering the detector, the vanadium dioxide film needs to complete the phase transition before the laser interferes the detector. The speed of film temperature rise and the rate of phase change are particularly important. In order to study the rate of film temperature rise, the experimental system as shown in figure 3 is designed, and a laser pulse led phase transition rate of vanadium dioxide is studied.
Fig. 3 A schematic diagram to measure the phase transition rate of vanadium oxide.

In the figure, Nd:YAG pulse laser is used as a film phase transition excitation source with high power. The laser will emit a single pulse of high energy, which will cause the vanadium oxide film phase transition happen under the action of this pulse. The wavelength of Nd:YAG laser is 1064nm. A filter was added to the optical path to prevent the laser beam of Nd:YAG laser from entering the detector. The semiconductor laser in the graph emits continuous light, which is mainly used to verify the phase change speed. Its energy is very weak, and the heating effect on the film phase transition is weak so that it will be negligible. The time of temperature rise phase transition and phase transition recovery time were estimated by using a filter to observe the wave variation of the wavelength of the semiconductor laser. Nd:YAG laser parameters are as follows: the output wavelength $\lambda=1064$nm and the pulse width is about 10-20ns, and the spot radius is 2mm. The parameters of the semiconductor laser are as follows: the output wavelength is about 532nm green light, the laser power density is about 80mW/cm$^2$, and the power stability is $\pm 3\%$.

The LabMax To high-speed photodetector was adopted to receive the laser which passed the VO2 film, and its response wavelength includes 532nm, 1064nm, 3100nm and 10.6μm. The TDS3054B oscilloscope of Tektronix company is used to display and record data in real time. The sampling frequency is 5GHz. At the same time, in order to prevent stray light interference caused by scattering on the film surface, 532nm single-pass filter is added in front of the detector. Adjust the laser light and test the light spot area on the sample to achieve complete overlap. At the same time, to ensure the accuracy of the experiment, the whole experiment was carried out in the dark room.

The change curves of light transmittance were tested under different energy density lasers, as shown in figure 4. Which $\Delta T/T_1$ is the relative change rate of the numerical size, $T_1$ is the initial light transmittance with no exciting light irradiated on it. FIG. 53a shows the change curve of the light transmittance of 532nm at the time interval of 40μs. FIG. 53b shows the change curve of the light transmittance of 532nm at the time interval of 40μs.
Laser energy which was used in figure 4 is weak. These illuminations are 10mJ/cm², 20.6mJ/cm², 26mJ/cm². Due to its weak energy, there is no complete phase transition happened in the irradiation area, and only partial phase transition occurs, and the test light variation is small. It can't completely change, and it can't completely reflect the phase change speed.

In figure b, the energy of the laser beam is relatively strong, and the illumination of the three laser beams is 32mJ/cm², 40mJ/cm², 60mJ/cm². These three irradiations have caused the phase transition of vanadium oxide film, and the change of the light transmittance is also obvious, and the phase change is faster. After the laser pulse is over, the time required for the phase transition back to the semiconductor state is closely related to the incident pulse energy, and the film phase transition of low laser energy is faster. The experimental results agree with the simulation results.

We define the phase transition response time of the VO₂ film is the time from the initial moment to the moment phase transition fully happens. As shown in FIG. 4b, VO₂ film phase transition response time increases slightly with the increase of pulse laser energy density, but the overall change is small, and the minimum phase transition response time is around 14ns.

6. Summary
Some text. Vanadium dioxide film has a phase transition property near room temperature. When the pulse laser irradiates the vanadium dioxide film, the conditions of the phase transition of the vanadium dioxide film are related to the Sapphire base thickness, the thickness of the film and the power of the laser pulse.

Under the condition in this paper, when the energy of a single pulse reaches 30mJ, phase transition of the film of vanadium oxide coated on sapphire substrate will happen. According to the experimental results, the phase change response time of vanadium oxide film was about 14ns. The phase transition speed can meet the requirements of anti-laser interference.

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