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Theoretical analysis on the switching speed and driving power dissipation for optical switch based on VO_2 thin film

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ABSTRACT

Optical switches based on vanadium dioxide (VO_2) thin film have emerged as potential candidates for deployment in future optical transport networks, where switching speed and driving power dissipation will become increasingly important. This paper reviews the basic working principle of optical switch based on VO_2 thin film, and gives out the physical thermal model for optical switch based on VO_2 thin film, according to which the driving power dissipation and switching speed expressions of the optical switch are obtained in theory. These two theoretical expressions reveal some key factors determining the minimum necessary driving power dissipation and maximum switching speed and theoretically point the direction to reduce the necessary driving power dissipation of optical switch and improve the switching speed of this kind of it.

1. Introduction

With the development of optical communication system, optical switches are needed to have more and more excellent performance parameters such as high switching speed and low driving power dissipation. Due to their sharp transition in optical properties at the critical temperature of 68 °C [1], VO_2 thin films are very attractive for optical switching applications. Normally, VO_2 film is optically transparent in the semiconductor phase at low temperature and reflective in the metallic state at high temperature [2]. Because of its intrinsic thermo-chromic phase-transition characteristic, VO_2 is one of good optical-material candidates for optical switches in future and has successfully been applied to the fabrication of some optical switches by several researchers [3–8]. Although optical switches based on VO_2 film have potential excellent performance characteristics such as reliability and fabrication processing simplification, improvements are still required in the areas of high switching speed and low driving power dissipation, which is necessary for the next-generation optical communication network where the information transmission speed and capacity are vital.

Lee has pointed out that the driving power dissipation of an optical switch based on VO_2 film is relating to the phase transition temperature of the VO_2 film [9], and some other researchers have reported that the phase transition temperature of VO_2 film can be reduced by doping with metals [5], or adjusting the thickness of the film [6]. In our former report, we introduced that the lower phase transition temperature of VO_2 film could result in the lower power dissipation of the optical switch based on the VO_2 film and further indicated that the switching speed could be speedup by optimizing the structure of optical switch [10,11]. However, the strictly theoretical switching speed and driving power dissipation have not been disclosed yet.

In this paper, in order to get the theoretical grounds for fabricating high-performance optical switches, the driving power dissipation and switching speed expressions of optical switches based on VO_2 film are deduced on the physical thermal model of a typical optical switch based on VO_2 thin film. The two expressions can be used as the theoretical base for designing and fabricating VO_2 optical switches of low power consumption and high speed. In addition, we propose some kinds of successful technology in our laboratory to fabricate low-power and high-speed VO_2 optical switches according to these theoretical expressions.

2. Theoretical analysis for VO_2 optical switch

A typical electro-optical switch based on VO_2 thin film is schematically illustrated in Fig. 1 [7,8]. The optical switch consists of a substrate layer such as glass or silicon, a heat insulating buffer layer like Si_3N_4 or TiO_2, VO_2 thin film, and a pair of electrodes. Among the different parts of optical switch structure, the semiconductor-to-metallic phase transition characteristics of the

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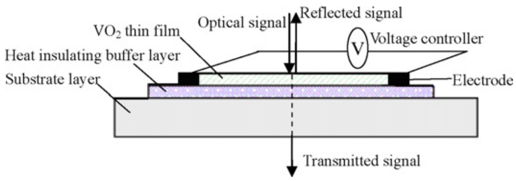

Fig. 1. Scheme of a typical electro-optical switch device structure based on VO_2 thin film.

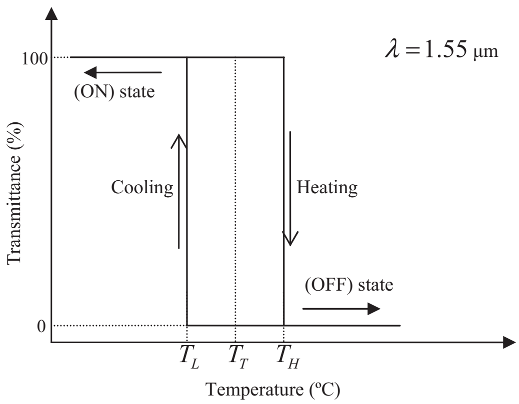

Fig. 2. Optical phase transition characteristic curve of the transmittance dependence on temperature at wavelength 1.55 μm for ideal VO_2 film.

VO_2 thin film are vital to achieve the function of the optical switch, which can be explained as follows. When the voltage applied to the pair of electrodes is up to a certain value which is controlled by the voltage controller, the VO_2 thin film is then heated to go into its metallic phase and exhibit an optical transmittance "off" state. On the other hand, the VO_2 thin film is cooled to go into its semiconductor phase and its transmittance increases to exhibit an optical transmittance "on" state while the reflectance decreases as the applied voltage decreases. Thus, the optical signal switching function can be easily realized through the phase transition from the semiconducting 'on' to the metallic 'off' state of the VO_2 thin film with the controllable voltage power supply.

Normally, the infrared (as an example of 1.55 μm wavelength) optical phase transition characteristic curve of an ideal VO_2 thin film in optical switch device can be approximatively illustrated in Fig. 2, where T_T is the optical phase transition temperature of the VO_2 thin film. The phase transition characteristic curve of the VO_2 thin film displays a hysteresis loop [10,11], which is $T_H - T_L$ wide and symmetrical between the heating and cooling branches (that is to say $T_H - T_T = T_T - T_L = (1/2)(T_H - T_L)$). The width of the hysteresis loop is within dozens of centidegrees and should be narrow for optical switch [8].

When the typical optical switch works, the temperature of the VO_2 thin film T depends on the energy exchange with its substrate heat reservoir at temperature T_s, infrared radiation power from the input optical signal and the heat reservoir P_s, and the voltage controlling power P produced by the driving voltage. The physical equivalent thermal model of the optical switch is shown in Fig. 3, in which g_{rad} is the radiation thermal conductance of the VO_2 thin film and g is the thermal conductance of the heat insulating buffer layer.

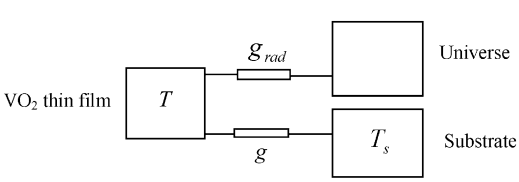

Fig. 3. Equivalent thermal model of optical switch.

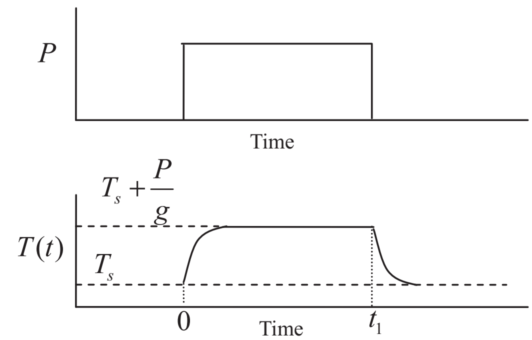

Fig. 4. Temperature response of the VO_2 thin film to single pulse of power supply.

If the heat capacity of the VO_2 thin film is c, the heat balance equation for the VO_2 thin film at temperature T can be expressed as

$$c\frac{dT}{dt} = P + \varepsilon P_s - g(T - T_s) - g_{rad}(T - T_s) \tag{1}$$

where ε is the absorptivity of the VO_2 thin film. Since $g_{rad} \ll g$ and $\varepsilon P_s \ll VI$ in present-day optical switch based on VO_2 thin film, the g_{rad} and εP_s terms can be ignored. Thus, the heat balance equation (1) can be transformed into

$$c\frac{dT}{dt} = P - g(T - T_s) \tag{2}$$

If P is zero for time $t < 0$ and P for time $t \geq 0$, we can this in the usual way to get

$$T(t) = T_s + \frac{P}{g}(1 - e^{-(t/\tau)}) \quad (t \geq 0) \tag{3}$$

which shows that the temperature of the VO_2 thin film in optical switch responds to the voltage controlling power P with an exponential thermal time constant $\tau = c/g$. After a period of many time constants, the temperature of the VO_2 thin film approaches the steady-state value

$$T(t \gg \tau) = T_s + \frac{P}{g} \tag{4}$$

If the voltage controlling power is P for time $t < t_1$ and zero for time $t \geq t_1$ and the temperature of the VO_2 thin film at time t_1 is $T(t_1)$, we also can solve Eq. (2) in a similar way to obtain

$$T(t - t_1) = T_s + [T(t_1) - T_s]e^{-((t-t_1)/\tau)} \tag{5}$$

Then the temperature of the VO_2 thin film can finally approach the steady-state value

$$T(t \gg \tau) = T_s \tag{6}$$

The temperature response of the VO_2 thin film to single pulse power supply is shown in Fig. 4. When the voltage controlling power is increased from zero to P, the temperature of the VO_2 thin film rises from T_s to $T_s + (P/g)$ with the exponential thermal time constant τ. Contrarily, the temperature of the VO_2 thin film will fall back toward the substrate temperature T_s with the same exponential time constant τ if the voltage controlling power P is reduced to zero at time t_1 and $T(t_1) = T_s + (P/g)$. Normally, the pulse interval of the power supply is long enough so that the temperature of the VO_2 thin film can approximately reach the steady-state value $T_s + (P/g)$ in the duration of power supply pulse. Thus, it can be said that the temperature of the VO_2 thin film at the time t_1 in Fig. 4 can be approximately looked as $T_s + (P/g)$ (that is $T(t_1) \approx T_s + (P/g)$).

In order to make the optical switch to realize its switching function, the steady-state value $T_s + (P/g)$ must be above the heating