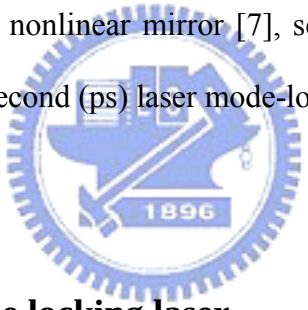
Chapter 1 Introduction

1-1 Introduction

1-1-1 Reviews of solid state laser mode locking

In past decades, there were many techniques to generate pulsed laser. Mode locking is most common methods to generate pulsed laser. It can be classified into two types: (1) active mode-locking and (2) passive mode locking. Actively mode-locking can be obtained by inserting an acoustic or an electro optic modulator into the laser cavity [1-4]. And there are plenty of methods to produce the passive mode locking laser. In femto-second regime, Kerr lens mode-locking [5-6] is the most common method to generate laser pulses, whereas, nonlinear mirror [7], semiconductor saturate absorber [8] etc. was usually used for pico-second (ps) laser mode-locking.



1-2 Motives

1-2-1 Applications of mode locking laser

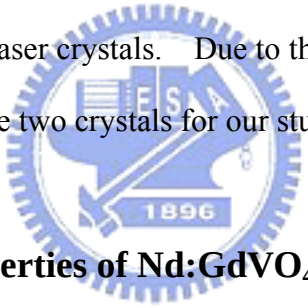
Pico-second pulses of micro joule energies with dozens of kHz pulse repetition frequency are demanded in several areas, e.g., micro machining, ophthalmology, dental surgery etc. Our goal of making high peak power ps pulses is to inject the high peak power laser pulses into photonic crystal fiber to produce supercontinuum (SC) [9-11] (white light generation). In order to effectively select any desired wavelength for material characterization, one could spectrally filter the broadband SC light provided that its spectrum is large enough, such as (white light) Z-scan [12-14] or pump probe measurement [15] of different band-gap material is demanded for different wavelengths. With low repetition rate, it's also good for material characterization to prevent the heat effect.

1-2-2 Reasons for choosing passive mode locking

Passive mode locking is quite easily to achieve by putting the passive (self-modulation) elements into the desired cavity, it is unlike the active mode locking which must rely more complicated external apparatus. Besides, the passive elements are maybe more than ten times cheaper as the active ones. Based on the above reasons, the passive mode locking is the best choice for our applications.

1-2-3 Merits of $Nd:GdVO_4$ and $Nd:LuVO_4$ laser crystals

Neodymiumdoped crystals (in particular Nd-doped vanadates) are particularly suitable for ps diode-pumped solid-state lasers (DPSSL), because of their high gain. As listed in the following table (Table 1.1) for the physical, optical, and fluorescence spectra of various Nd-doped vanadate laser crystals. Due to the superior properties of $Nd:GdVO_4$ and $Nd:LuVO_4$, we choose these two crystals for our study of DPSSL mode-locking.



1-2-3-1 The physical properties of $Nd:GdVO_4$ and $Nd:LuVO_4$

There are two main physical characters what one would particularly concern about, i.e., thermal expansion coefficient and specific heat. First, we list thermal expansion coefficient of three kinds of popular Nd:doped laser crystals [16] in Table 1.1. Thermal expansion coefficient should be as small as possible and less anisotropy. In Table 1.1, the thermal expansion coefficient along [001] representing for c-axis or Z direction is larger than that along [100] direction (a-axis or X–direction) by 5 to 7 times. The more apparent trend is shown in Fig. 1.1. The lower coefficient causes the less thermal lensing effect, this is why usually a-cut $Nd:LuVO_4$ and $Nd:GdVO_4$ crystals were used in the laser systems. Although $Nd:LuVO_4$ and $Nd:GdVO_4$ crystals are not the best ones in terms of thermal expansion among the Nd:doped laser crystals listed in Table 1.1, there are other aspects these crystals perform better than the others that will be discussed in the following.

Table 1.1 Thermal expansion coefficient[16]

Principal thermal expansion coefficients of crystals (unit 10^{-6} $^{o}C^{-1}$)

Crystal/directions	α[100]	α[001]	Ratio (c/a)
Nd:$LuVO_4$	1.6	9.1	5.7
Nd:YVO_4	1.96	7.827	4.0
Nd:$GdVO_4$	1.05	7.419	7.1

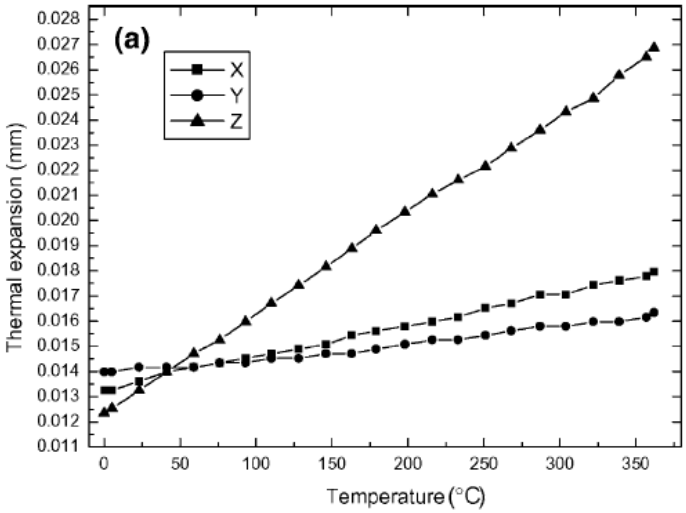


Fig. 1.1 Thermal expansion of Nd:$LuVO_4$ crystal along X-, Y - and Z-axis.

Specific heat, the ratio of converting the absorbed energy to the change in temperature, is also one of important factors that affect the damage threshold of a laser crystal. Energy production and storage has created a demand for construction materials. It can be affected by all temperature-dependent phenomena, for instance, the lattice vibration spectrum, electron distribution, interaction of particles, and phase transitions. The more specific heat, the more resistance to laser damage is since a rise in temperature by laser irradiation with the mechanisms is responsible for laser damage.

From Fig. 1.2, the specific heat changing linearly with temperature in Nd:$GdVO_4$ is unlike Nd:$LuVO_4$ which is almost independent of temperature. In spite of Nd:$GdVO_4$ is good for high power operation for pass five years, Nd:$LuVO_4$ should have a better

performance. The specific heat of Nd:$LuVO_4$ is 0.45 J g^{-1} K^{-1} at 330 K equivalent to 31.6 cal mol^{-1} K^{-1}. It is a little bit smaller than that of Nd:$GdVO_4$ crystal (32.6 cal mol^{-1} K^{-1}) at 330 K. We conclude that Nd:LuVO4 and Nd:GdVO4 both possess high damage threshold which can maintain a small temperature gradient while being irradiated by a laser system.

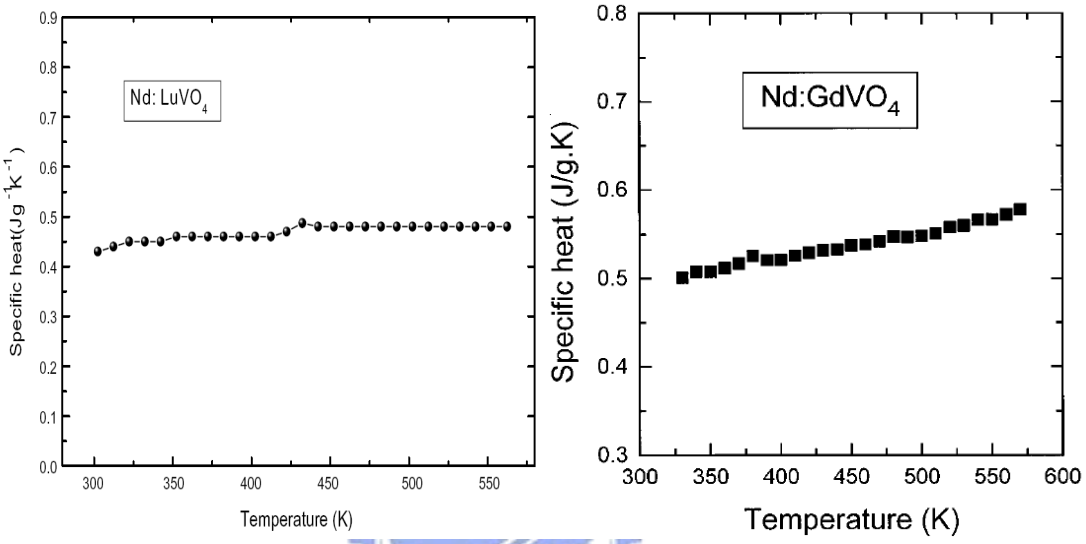


Fig. 1.2 Temperature dependence of the specific heat of Nd:LuVO4 and Nd:$GdVO_4$ crystal.

1-2-3-2 Fluorescence spectra of Nd:$GdVO_4$ and Nd:$LuVO_4$

Some optical parameters draw our attention such as broad absorption and large stimulated emission cross section [17-20]. The fluorescence times were shown in Table 1.2 as well as Figs. 1.3 and 1.4. This part is the most critical point why we have selected Nd:$GdVO_4$ and Nd:$LuVO_4$ over so many crystals. Although Nd:YVO_4 has large stimulated absorption and emission cross section, Nd:$LuVO_4$ is the largest one. The higher absorption cross section means that it has good probability to absorb pumping light, and so as the higher stimulated emission cross section that gives the larger lasing power. Therefore, we would expect that Nd:$LuVO_4$ should have better performance.

Table 1.2 Stimulated absorption and emission cross section of Nd doped vanadates crystals

Title	$Nd:LuVO_4$	$Nd:YVO_4$	$Nd:GdVO_4$	Nd:YAG	Nd:YLF
σ_{abs} 800nm	69	57	52	6.1	4.8
$\Delta\lambda_{abs}$(nm)	1.5	1.4	1.6	1.3	1.5
σ_{em} ~1064nm	146	135	76	27	1.8 at 1047nm
σ_{em} ~1320nm	43	38	18	5.2	5.4 at 1313nm
τ_{fluo}(μs)	82	76	90	240	520

*All cross section are expressed in units of $10^{-20}cm^2$.

The absorption spectra of $Nd:GdVO_4$ and $Nd:LuVO_4$ are clearly shown in Fig. 1.3. Due to optical pumping using 808 nm diode laser, the main absorption peak near 808 nm is our interest. In addition, both of $Nd:GdVO_4$ and $Nd:LuVO_4$ show broad absorption bandwidth.

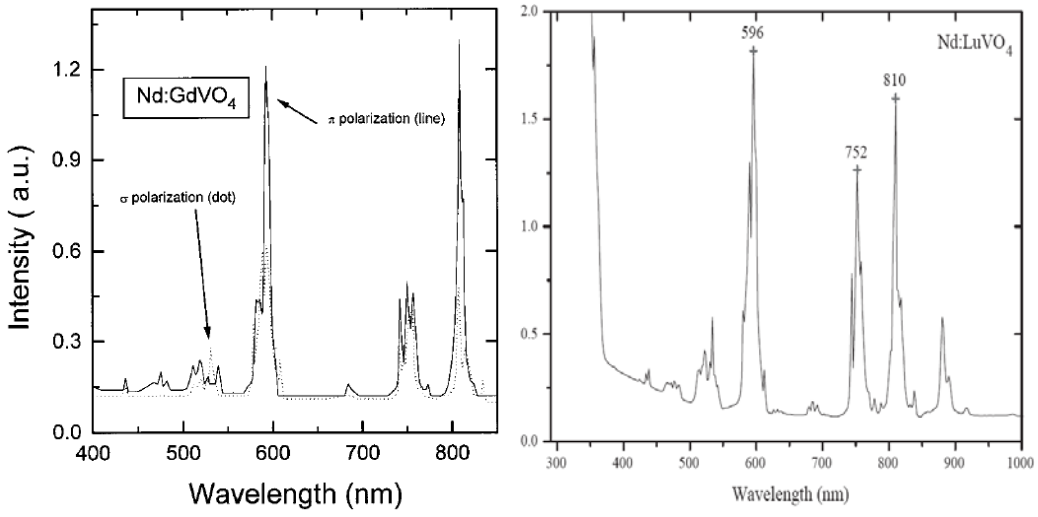


Fig. 1.3 Absorption spectrum of a Nd:GdVO4 crystal from 400 to 850 nm (left) and absorption spectrum of Nd:LuVO4 crystal from 300nm 1000nm (right) at room temperature.

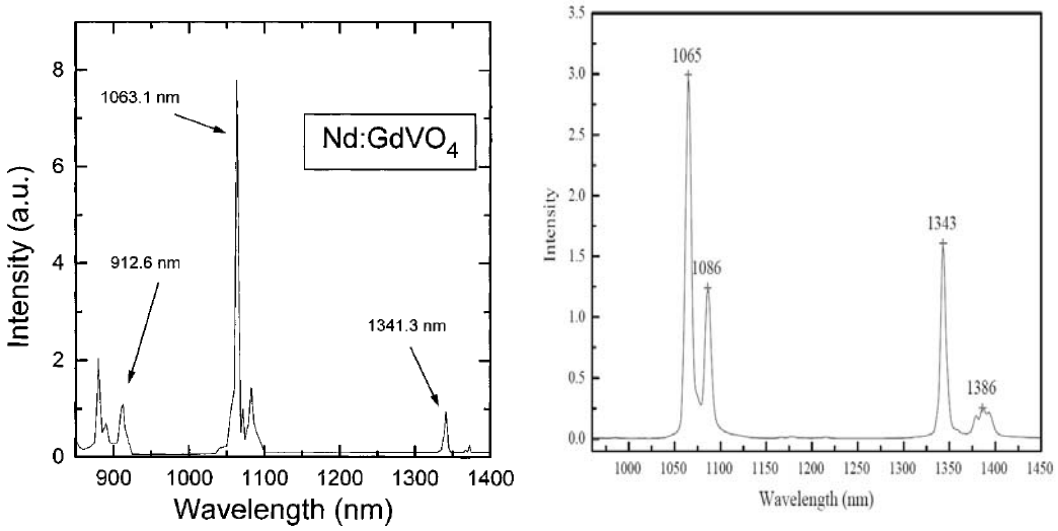


Fig. 1.4 Fluorescence spectrum of a Nd:GdVO4 crystal from 850 to 1400 nm (left) and fluorescence spectrum of a Nd:LuVO4 crystal from 900 to 1450 nm (right) at room temperature.

Each peak of the fluorescence spectra is almost the same for two crystals, but the main peak of Nd:$LuVO_4$ at 1065.8 nm slightly shifts related to the peak at 1063.1 nm for Nd:$GdVO_4$. Other peaks at 912.6, 1343, and 1086 nm are inferiority absorption peaks for Raman lasers. In our research, we only focus on the center lasing wavelength around 1064 nm.

1-3 Organization of Thesis

In this thesis, we will demonstrate two most general methods to create the passive mode locking laser in the pico-second regime that is suitable for Nd:doped laser crystals: (1) mode-locking by semiconductor saturable absorber mirror (InGaAs) in Chapter 3; (2) nonlinear mirror mode-locking contained frequency double crystal in Chapter 4; and (3) in order to generate the high peak power and low repetition rate laser, we combine the merits of both (1) and (2) for the third method --- dual mode-locked technique in Chapter 5. To prevent too much mode locking pulses within a Q-switching envelope (shorter Q-switching

pulse width) in dual mode locking, we do more work by inserting a Cr:YAG saturable absorber into the laser cavity in Chapter 6. Finally, we give a brief conclusion and what we can apply these results for in Chapter 7.

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