Design and Simulation of Q-Switching and Mode-Locking Nonlinear Mirror for Frequency-Doubled DPSS Nd:YAG Laser Output

In this work, multilayer reflection coating analysis has been employed for designing and simulating nonlinear mirror to be used for Q-switching and mode-locking of frequency-doubled DPSS Nd:YAG laser using composite crystal (DPM010X). It was found that the optical reflection greatly depends on the type of nonlinear crystal and dichroic material used, the type of the refractive index (ordinary or extraordinary), direction of propagation inside the nonlinear material, optical thickness and the number of anti-reflection coating layer used. The calculated refracted index was found to be 2.232 for the 1064nm wavelength for LNBO3 crystal and 1.655 for 1064nm for the BBO crystal. The results show that the reflectivity reaches the best value when the refractive index difference between the anti-reflection coating layers is small, and increasing the number of such layer. The calculated phase-match angle is equal to 13.75177°.

Keywords: Nd:YAG laser, Second Harmonic Generation, Nonlinear Mirror, Mode Locking

Received: 19 July 2011, Revised: 15 October 2011, Accepted: 22 October 2011

1. Introduction:

Diode-Pumped Solid State (DPSS) lasers are the ideal laser tools of machining, material processing, spectroscopy, wafer inspection, light show, medical diagnostics and other applications. The DMP110X composite crystals which combine the vanadate (Neodinium Doped Yttrium Aluminum Garnet) Nd:YAG and non-linear crystals. The DPM crystals are mainly used for low power applications, for example, the Green Laser Pointers. Here are some systems that will get you some green light without either expensive crystals or the need for complex mounting and infinite alignment fiddling, as shown in Fig. (1). I am, of course, talking about the use of a hybrid (also called composite) vanadate-non-linear crystal. A non-linear mirror consisting of a non-linear crystal and a dichroic output coupler are used to mode-lock (passively) an Nd:YAG laser, pumped by a diode laser.

Fig. (1) Schematic diagram of the (DPM) composite crystal [1]

2. Theory

The Solid State (SS) Laser uses a solid crystalline material as the lasing medium and is usually optically pumped. Nd:YAG is one of the most efficient laser crystal for diode laser-pumped solid-state lasers especially used in end-pumping configurations. This laser crystal is finding much use in frequency doubled green laser pointers and other small diode laser modules.

Second Harmonic Generation (SHG) occurs an intense light beam of angular frequency ω passing through an appropriate crystal (e.g. KTP) generates a light beam of double the frequency, ω2. If E is the electric field in the light wave, then the induced polarization P becomes a function of E and can be written as

\[ P = \varepsilon_0 \chi_{ij} E \sin(\omega t) - \frac{1}{2} \varepsilon_0 \chi_{ij} E \cos(2\omega t) + \frac{1}{2} \varepsilon_0 \chi_{ij} E, \]

where \( \chi_1, \chi_2 \) and \( \chi_3 \) are the linear, second-order and third-order susceptibilities.

SHG is based on a finite \( \chi_2 \) coefficient in which the effect of \( \chi_3 \) is negligible. The first term is the fundamental, second is the second harmonic and third is the dc term. The second harmonic (2ω) oscillation of local dipole moments generates secondary second harmonic (2ω) waves in the crystal as shown in Fig. (2). However, the crystal will normally possess different refractive indices n(ω) and n(2ω) for frequencies ω and 2ω. The condition that the second harmonic waves must travel with the same phase velocity as the fundamental wave to constitute a second harmonic beam is called phase matching and requires n(ω) = n(2ω). One method is to use a birefringent crystal as these have two refractive indices: ordinary index no and extraordinary index ne. Suppose that...
along a certain crystal direction at an angle $\theta$ to the optic axis, $n_D(2\omega)$ at the second harmonic is the same as $n_D(\omega)$ at the fundamental frequency: $n_D(2\omega)=n_D(\omega)$. This is called index matching and the angle $\theta$ is the phase matching angle. To separate the second harmonic beam from the fundamental beam, something like a diffraction grating, a prism or an optical filter (such as anti reflection coating) will have to be used at the output as. The optical matrix approach was employed for N-layer design of antirefection coating the main idea of this method is matching the E and H fields of the incident light on the interfaces of the multilayer optical coatings. The matrix relation defining the N-layer antirefection problem is given by [1]

$$
\begin{bmatrix}
B \\
C
\end{bmatrix} = \prod_{q=1}^{m} \begin{bmatrix}
\cos \delta_q & i \sin \frac{\delta_q}{n_q} \\
\sin \delta_q & \cos \frac{\delta_q}{n_q}
\end{bmatrix} \begin{bmatrix}
1 \\
1
\end{bmatrix}
$$

(1)

where $B$ and $C$ are total electric and magnetic field amplitudes of light propagation in the medium. The optical admittance is given by the ratio

$$
Y = \frac{C}{B}
$$

(2)

where $n$ is the refractive index of the layer and $\delta$ is the phase thickness given by

$$
\delta = \frac{2\pi n d_q}{\lambda}
$$

(3)

with the physical thickness of the layer being $d_q$. Then the reflection coefficient $r$ and the reflectivity $R$ are, respectively, given by [1]

$$
R = r^2 = \frac{n_0 - Y}{n_0 + Y}
$$

(4)

where $r$ is the reflectance.

The laser is operated in actively Q-switched mode to obtain nanosecond pulse by inserting an acousto-optic Q-switch in the laser cavity [2]. Whereas, nonlinear mirror (NLM) technique is used to realize passive mode-locking for the generation of picosecond pulses. In NLM systems, a frequency doubling nonlinear crystal (NLC) is incorporated in the laser cavity and placed near a dichroic mirror used in place of the usual output coupler. The dichroic mirror partially reflects the fundamental wave (FW) but totally reflects the second harmonic (SH) beams. The FW generates SH in its first pass and if the SH beam experiences a proper phase shift with respect to the FW beam, the SH power is almost totally reconverted into FW during the second pass through the NLC. As the second harmonic generation (SHG) is a second order nonlinear optical process, the NLC along with the dichroic mirror behaves as a NLM having an intensity dependent reflection coefficient. Under this condition the laser losses decrease with an increase in the peak power of the FW beam and so the behavior is the one of a fast saturable absorber. The nonlinear mirror initiates the generation of ultrashort pulse. The advantage of this mode-locking over semiconductor saturable absorber is its simplicity in design and can be operated in wide spectral range [3].

3. Experiment

(DPM1101) composite crystal in Diode-Pumped Solid State (DPSS) lasers system has been chose for designing the required model. The use of hybrid or composite crystals represents by far the easiest way to construct a low power green DPSS laser. They virtually eliminate fiddling as a pastime since the HR, Nd:YAG (vanadate), non-linear crystal, and OC mirrors are all permanently aligned. For many applications, no additional optics is required. Such systems are used mainly for SHG, which involve two fundamental mode photons[4].
The specifications of the DPM crystal 1101 are summarized by:

- **Size and finish:** The DPM0101 is approximately 1x1x2.5 mm (WxHxL).
- **Vanadate doping and thickness:** The doping is probably 3 percent and the thickness is 0.5 mm.
- **Vanadate features and optical properties :** The main feature of the vanadate is:
  1. Low lasing threshold and high slope efficiency.
  2. Large stimulated emission cross-section at lasing wavelength.
  3. High absorption over a wide pumping wavelength bandwidth.
  4. Optically uniaxial and large birefringence emits polarized laser. Its Fluorescence Spectra Curve are shown below in Fig. (3) [5].

4. **Simulation in MATLAB:**

The simulation of the reflection in MATLAB have been the main assignment of this work, the reflectivity of non linear mirror have been simulated with multilayer antireflection coating after chose the proper type of material for both high and low index of reflection which must has suitable absorption, good adhesion, low stress, hardness and low cost and easy preparation. The program optimize at \(\lambda_{c}=532\) nm central wave length for visible and near infrared spectral region (300-1100) nm. The parameters of antireflection are:

1. Optical thickness for each layer
2. Refractive index for each layer coating and substrate

The material must be select that low wave absorption, homogeneity, high packing density, good adhesion, low stress, hardness, and ability survive in deferent environmental, low cost and easy preparation [7-8].

5. **Results and Discussion**

Reflection was taken as function of the wave length for different type of coated material for non linear mirror as shown below. Non linear crystal was taken as substrate material with refractive index of (2.2082) for the (KNbO₃) and (1.6551) for the (BBO) crystal, reflection has been simulated with central wavelength (532nm) which is the second harmonic one , in the range begun from visible up to near IR range in multilayer anti-reflection technique, as shown in the following simulated figures. The thickness of the layer was taken equal to 0.25 of wavelength because it’s the perfect one .Different type of dichroic material were taken in the simulation in order to reach to the perfect one.

In all simulated figures below, N values strongly affected on the reflectivity .increasing N increased proper choice to reach to the required situation for example in our design for the non linear mirror HR was needed for the 532nm and HT for the 1064nm [7] this can be take with N=12 in all curve, we notes also that there are much difference in the reflectivity behavior seen resulting from changing optical thickness of the anti-reflected coating that’s affected on the design requirement which is one of the most important factor that’s limit our design and make as carefully choosing its value this not only note but its really bright point leading us to choose the good design parameter if we compares between all figures with Fig. (10) by which we can believe that 0.25 optical thickness value is the more suitable one for this work. finally the proper choice for the antireflection layer material is critical point not only because its refractive index which effect on reflectivity value but its limit the life time of our design because the other property of it, such as stress, hardness and ability to survive in different environmental, cost and preparation ability.
Table [1] optical properties of the Vanadate [6]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lasing Wavelengths</td>
<td>914nm, 1064 nm, 1342 nm</td>
</tr>
<tr>
<td>Crystal class</td>
<td>positive uniaxial, n₁= n₃= n₅, n₂= n₄</td>
</tr>
<tr>
<td>Sellmeier Equation (for pure YAG crystals):</td>
<td>n₁²=3.77834+0.069736/(λ² - 0.04724) - 0.0108133λ²</td>
</tr>
<tr>
<td></td>
<td>n₂²=4.59905+0.110534/(λ² - 0.04813) - 0.0122076λ²</td>
</tr>
<tr>
<td>Thermal Optical Coefficient</td>
<td>dn/λdλ=8.5x10⁻⁷/K, dn/λdλ=3.0x10⁻⁷/K</td>
</tr>
<tr>
<td>Stimulated Emission Cross-Section</td>
<td>25.0x10⁻²⁰ cm², @ 1064 nm</td>
</tr>
<tr>
<td>Fluorescent Lifetime</td>
<td>90 µs (about 50 µs for 2 atm% Nd doped) @ 808 nm</td>
</tr>
<tr>
<td>Absorption Coefficient</td>
<td>31.4 cm² @ 808 nm</td>
</tr>
<tr>
<td>Absorption Length</td>
<td>0.32 mm @ 808 nm</td>
</tr>
<tr>
<td>Diode Pumped Optical to Optical Efficiency</td>
<td>&gt; 60%</td>
</tr>
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</table>

Optical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency Range</td>
<td>400 - 4500 nm</td>
</tr>
<tr>
<td>Absorption loss</td>
<td>≤1%/cm at 1064nm</td>
</tr>
<tr>
<td>Damage threshold</td>
<td>≤4J/cm² at 527nm (500ps, single pulse)</td>
</tr>
<tr>
<td></td>
<td>≤6J/cm² at 1054nm (700ps, single pulse)</td>
</tr>
<tr>
<td>Principal Axes &amp; Crystallographic Axes:</td>
<td>x U c; y U a; z U b (ie. n₁=n₂=n₅)</td>
</tr>
<tr>
<td>Typical Refractive Indices</td>
<td>i  ii  iii  (n₁) (n₂) (n₃) (n₄) (n₅)</td>
</tr>
<tr>
<td>i</td>
<td>430nm  2.4145  2.4974  2.2771</td>
</tr>
<tr>
<td>ii</td>
<td>532nm  2.3223  2.3813  2.2022</td>
</tr>
<tr>
<td>iii</td>
<td>860nm  2.2372  2.2784  2.1338</td>
</tr>
<tr>
<td>i</td>
<td>1064nm 2.2195  2.2576  2.1194</td>
</tr>
<tr>
<td>Sellmeier Equations: ( l in mm)</td>
<td>n = 4.4208 + 0.10044/(λ² - 0.054084) - 0.019592λ²</td>
</tr>
<tr>
<td></td>
<td>n = 4.8355 + 0.12839/(λ² - 0.056342) - 0.025379λ²</td>
</tr>
<tr>
<td></td>
<td>n = 4.9873 + 0.15149/(λ² - 0.064143) - 0.028775λ²</td>
</tr>
</tbody>
</table>

Nonlinear Optical Properties

| Nonlinear Optical Coefficients:               | d₁₁=-15.8pm/V, d₁₂=-18.3pm/V at 1064 nm |
| The Shortest SHG Wavelength:                 | 425 nm (type I NGPM, y-cut or a-cut)      |
| Acceptance Angle for Type I SHG of 1064 nm:  | D₄₃ = 0.24 mrad-cm (internal)             |

Fig. (4) Reflection as function of wavelength for (TiO₂ as high index) and (MgO as low index) coated material and (KNO₃) as non linear crystal. (A) simulated figure with optical thickness (N=4,6,8) for both high and low coated layer. (B) simulated figure with optical thickness (N=8,10,12) for both high and low coated layer.

Fig. (5) Reflection as function of wavelength for (MgO as high index) and (MgF₂ as low index) coated material and (KNO₃) as non linear crystal.

Fig. (6) Reflection as function of wavelength for (TiO₂ as high index) and (MgO as low index) coated material and (BBO) as non linear crystal.
**6. Conclusion:**

We can say that the best choice for the N is 12 with 0.25 optical layer thickness by which the design reaches the optimum requirement and the material used as a layer in Fig. (9) is the best because it makes design approaches the required as the reflectivity for the 532nm is 93% and for the 1064nm is 18% and the band of tuned wave length is very small. All these make this design parameter is nearly the perfect.

**References**


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This article was reviewed at Department of Physics, Faculty of Science, Tsinghua University, CHIN, and Department of Physics, College of Education, The Iraqi University, Baghdad, IRAQ.