

Aseel A. Al-Sharify

Department of Laser and  
Optoelectronics Engineering,  
University of Technology,  
Baghdad, IRAQ

# 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 the nonlinear crystal and dichroic material used, the type of the refractive index (ordinary or extra-ordinary), 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 LINBO<sub>3</sub> 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  
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## 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 DPM110X composite crystals which combine the vanadate (Neodimium 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.

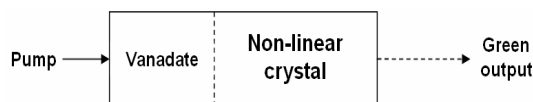


Fig. (1) Schematic diagram of the (DPM) composite crystal [1]

## 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  $\omega$  passing through an appropriate crystal (e.g. KTP) generates a light beam of double the frequency,  $2\omega$ . 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

$$P = \epsilon_0 \chi_1 E_0 \sin(\omega t) - \frac{1}{2} \epsilon_0 \chi_2 E_0^2 \cos(2\omega t) + \frac{1}{2} \epsilon_0 \chi_3 E_0^3$$

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 ( $2\omega$ ) oscillation of local dipole moments generates secondary second harmonic ( $2\omega$ ) waves in the crystal as shown in Fig. (2). However, the crystal will normally possess different refractive indices  $n(\omega)$  and  $n(2\omega)$  for frequencies  $\omega$  and  $2\omega$ . 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  $n(\omega) = n(2\omega)$ . One method is to use a birefringent crystal as these have two refractive indices: ordinary index  $n_o$  and extraordinary index  $n_e$ . Suppose that

along a certain crystal direction at an angle  $\theta$  to the optic axis,  $n_e(2\omega)$  at the second harmonic is the same as  $n_o(\omega)$  at the fundamental frequency:  $n_e(2\omega)=n_o(\omega)$ . 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 antireflection 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 antireflection problem is given by [1]

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

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

$$Y = \frac{C}{B} \quad (2)$$

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

$$\delta = \frac{2\pi n d_q}{\lambda} \quad (3)$$

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

$$R = r r^* \quad (4)$$

where r is the reflectance

$$r = \frac{n_0 - Y}{n_0 + Y} \quad (5)$$

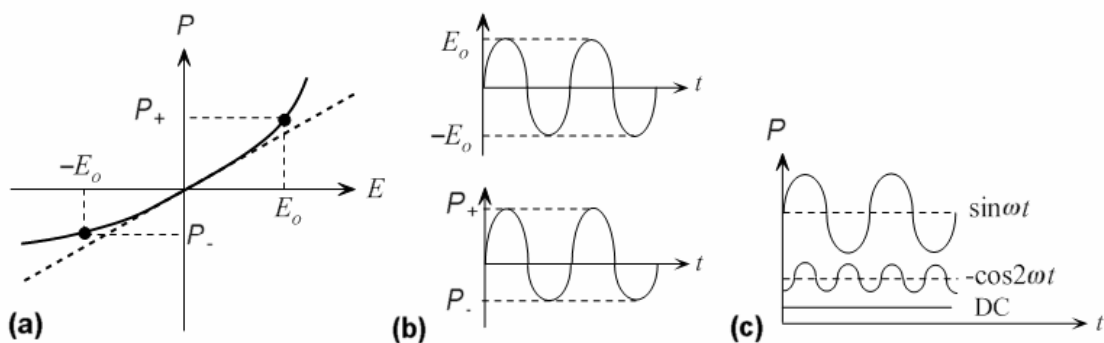


Fig. (2) (a) Induced polarization vs. optical field for a nonlinear medium. (b) Sinusoidal optical field oscillation between  $E_o$  result in polarization oscillation between  $P_+$  and  $P_-$ . (c) The polarization oscillation can be represented by sinusoidal oscillations at angular

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

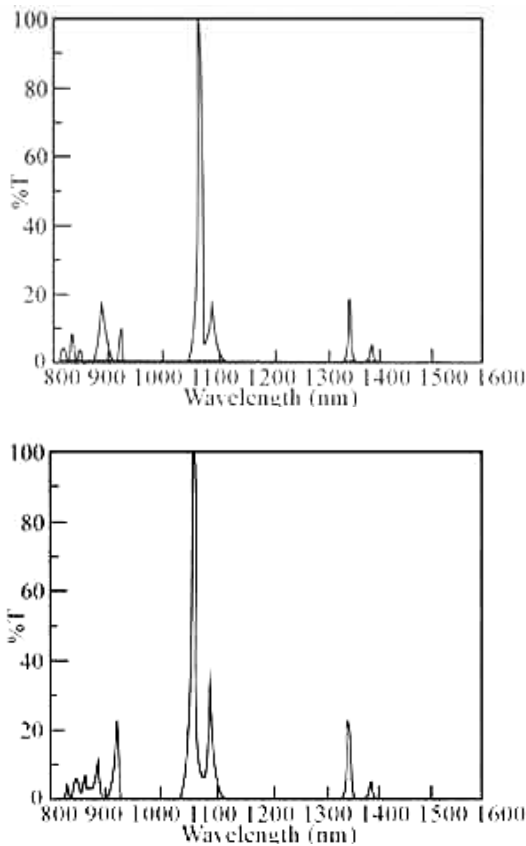
in the peak power of the FW beam and so the behavior is the one of a fast saturable absorber. The nonlinear mirror initiates the generation of ultrashort pulse. The advantage of this mode-locking over semiconductor saturable absorber is its simplicity in design and can be operated in wide spectral range [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].



**Fig. (3) Fluorescence Spectra Curve of the vanadate**

Because of its large stimulated emission cross section at 1.34  $\mu\text{m}$ , Nd:YAG is also an efficient laser crystal for diode laser-pumped 1.3  $\mu\text{m}$  laser [5]. By using the compact design of Nd:YAG non linear crystal crystals, high power green or red light output can be generated in a diode laser pumped Nd:YAG laser. The optical properties of the Vanadate are shown in table (1) [6].

**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  $\lambda_0=532\text{ nm}$  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 (  $\text{KNbO}_3$ ) 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]

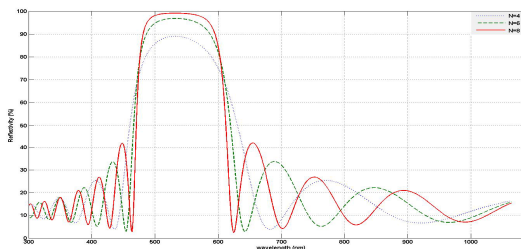
Lasing Wavelengths	914nm, 1064 nm, 1342 nm
Crystal class	positive uniaxial, $n_o=n_a=n_b$ , $n_e=n_c$
Sellmeier Equation (for pure YAG crystals):	$n_o^2=3.77834+0.069736/(\lambda^2 - 0.04724) - 0.0108133.\lambda^2$ $n_e^2=4.59905+0.110534/(\lambda^2 - 0.04813) - 0.0122676.\lambda^2$
Thermal Optical Coefficient:	$dn_a/dT=8.5 \times 10^{-6}/K$ , $dn_e/dT=3.0 \times 10^{-6}/K$
Stimulated Emission Cross-Section	$25.0 \times 10^{-19} \text{ cm}^2$ , @1064 nm
Fluorescent Lifetime	90 $\mu\text{s}$ (about 50 $\mu\text{s}$ for 2 atm% Nd doped) @ 808 nm
Absorption Coefficient	$31.4 \text{ cm}^{-1}$ @ 808 nm
Absorption Length	0.32 mm @ 808 nm
Diode Pumped Optical to Optical Efficiency	> 60%

Optical Properties

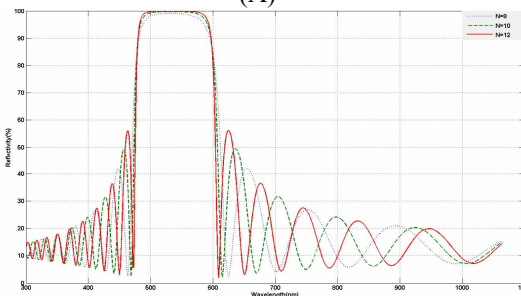
Transparency Range:	400 - 4500 nm			
Absorption loss:	<=1%/cm at 1064nm			
Damage threshold:	<=4J/cm <sup>2</sup> at 527nm (500ps, single pulse) <=6J/cm <sup>2</sup> at 1054nm (700ps, single pulse)			
Principal Axes $\hat{U}$ Crystallographic Axes:	$x \hat{U} c$ ; $y \hat{U} a$ ; $z \hat{U} b$ (ie. $n_b > n_a > n_c$ )			
Typical Refractive Indices:	ij	$n_a$ ( $n_y$ )	$n_b$ ( $n_z$ )	$n_c$ ( $n_x$ )
ii	430nm	2.4145	2.4974	2.2771
ii	532nm	2.3223	2.3813	2.2022
ii	860nm	2.2372	2.2784	2.1338
ii	1064nm	2.2195	2.2576	2.1194
Sellmeier Equations: (l in mm)	$n = 4.4208 + 0.10044/(l^2 - 0.054084) - 0.019592l^2$ $n = 4.8355 + 0.12839/(l^2 - 0.056342) - 0.025379l^2$ $n = 4.9873 + 0.15149/(l^2 - 0.064143) - 0.028775l^2$			

Nonlinear Optical Properties

Nonlinear Optical Coefficients:	$d_{31}=-15.8\text{pm/V}$ , $d_{32}=-18.3\text{pm/V}$ at 1064 nm
The Shortest SHG Wavelength:	425 nm (type I NCPM, y-cut or a-cut)
Acceptance Angle for Type I SHG of 1064 nm:	$Dq = 0.24 \text{ mrad}\cdot\text{cm}$ (internal)



(A)



(B)

Fig. (4) Reflection as function of wavelength for (TiO<sub>2</sub> as high index ) and (MgO as low index) coated material and ( KNbO<sub>3</sub> )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.

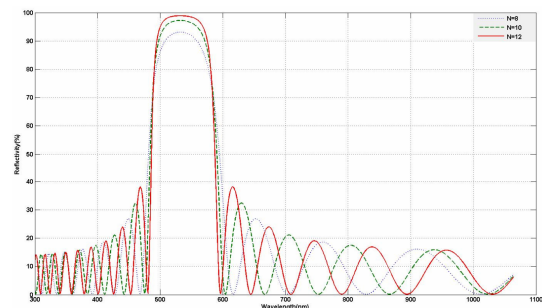


Fig. (5) Reflection as function of wavelength for (MgO as high index) and (MgF<sub>2</sub> as low index) coated material and (KNbO<sub>3</sub>) as non linear crystal

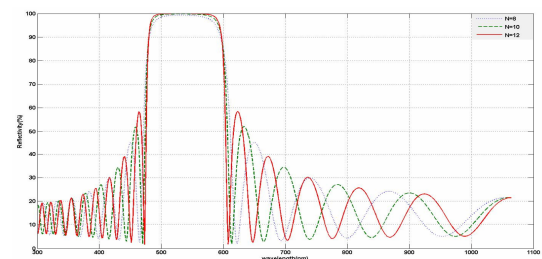


Fig. (6) Reflection as function of wavelength for (TiO<sub>2</sub> as high index) and (MgO as low index) coated material and (BBO) as non linear crystal

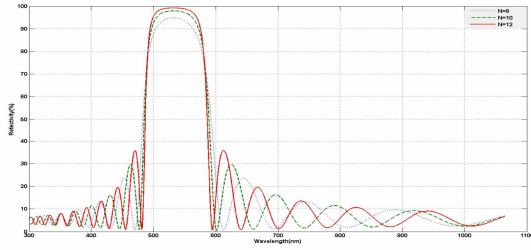


Fig. (7) Reflection as function of wavelength for (MgO as high index) and (MgF<sub>2</sub> as low index) coated material and (BBO) as non linear crystal

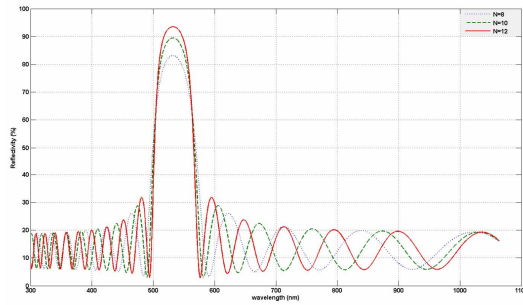


Fig. (8) Reflection as function of wavelength for (ZrS as high index) and (SiO as low index) coated material and (BBO) as non linear crystal

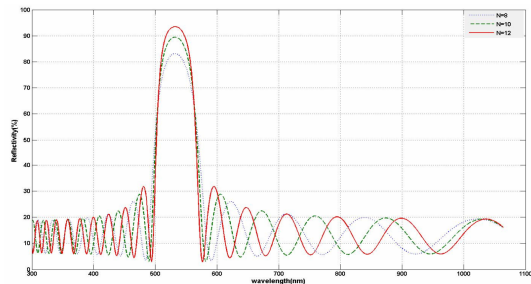


Fig. (9) Reflection as function of wavelength for (ZrO<sub>2</sub> as high index) and (HfO<sub>2</sub> as low index) coated material and (BBO) as non linear crystal

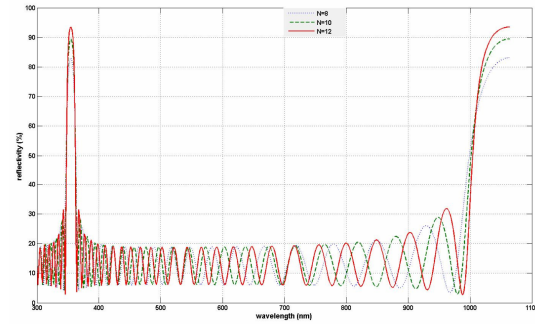


Fig. (10) Reflection as function of wavelength for (ZrO<sub>2</sub> as high index) and (HfO<sub>2</sub> as low index) coated material and (BBO) as non linear crystal with half wavelength thickness

**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**

- [1] Macleod, H.A., “Thin-Film Optical Filters”, 2<sup>nd</sup> ed., 2001, Bristol Co., Ltd. (UK).
- [2] P.K. Datta et al., *Optics Express*, 12, 4041 (2004).
- [3] T.R. Schibli et al., *Appl. Phys. B*, 70, 41 (2002).
- [4] M. Lipinski et al., *Materials Science –Poland*, 24(4) (2006) 13-22.
- [5] M.M. Fejer et al., *IEEE J. Quantum Electron.*, QE-28, 2631–2654 (1992).
- [6] R. Dabu, C. Fenic and A. Stratan, *Optica Applicata*, XXVI(3), 171–183, (1996).
- [7] H.E. Selhofer and R. Linsbod, *Appl. Opt.*, 41 (2002) 756.
- [8] J.M. Bennett, et al., *Appl. Opt.*, 28 (1989) 3303.

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