Theoretical model of fiber coupling diode end-pumped intra-cavity frequency-doubling lasers

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Abstract: Based on Paolo Laporta's fiber coupling diode end-pumped IR laser model, theoretical model for diode end pumped intra-cavity doubling frequency laser is built up. The model not only includes resonator parameters, but also includes diode pumping power and spot size inside the active material. An experimental set up is designed to verify the theoretical model. The theoretical model tally with the experimental results very well. The theoretical model can be used in self-frequency doubling, as well as intra-cavity frequency doubling.

Key words: resonator model, diode end pumped, intra-cavity frequency doubled

1. Introduction

The rapid developments of infrared diode lasers and new laser materials have made the diode pumped solid state lasers (DPSSL) efficient and reliable sources of coherent light. By now, these properties have led to the commercial availability of a number of systems. Diode pumped solid state laser emits in the near IR. However, many technical applications, as laser marking on metals, higher density optical storage and precision interferometric measurements, rather require shorter wavelengths.

Currently, four principally different approaches are used to generate visible light with DPSSL : 1) There has been considerable progress in new up-conversion laser materials, but still very few examples of visible emission at room temperature are known, in none of these cases exclusively pumped with laser diode. 2) In terms of wavelength flexibility, efficiency, and output power, the traditional way of second harmonic generation (SHG) in an external build-up cavity has to be mentioned. The disadvantage of this otherwise straightforward method is the requirement for servo control of either the length of the solid state laser cavity or of the external conversion cavity. 3) Intra-cavity SHG takes advantage of the high power of the fundamental for efficient conversion and simultaneously circumvents the servo problem. However, a non-linear crystal placed in the laser cavity causes passive losses for the fundamental by residual reflectivity, spurious absorption, and scattering. If the non-linear crystal is not of excellent optical quality the intracavity power may be severely reduced as compared to the unload cavity, which results in inefficient SHG. Another disadvantage should not be underestimated, that is the complexity of the two-crystal setup with its correspondingly difficult alignment. (4) An elegant way to avoid most of the problems listed above is to incorporate both, the properties of a laser crystal and the properties of a non-linear crystal in one crystal. A laser based on such a crystal is usually called a self -frequency doubling (SFD) laser[1,2].

The methods (3) and (4) are intra-cavity frequency doubled. There is little theoretical model to describe the fiber coupling diode end-pumped intra-cavity frequency-doubling lasers. This paper tries to build up a theoretical model that include parameters affecting the green laser power as much as possible.

2. Theory model of fiber coupling diode end-pumped intra-cavity frequency-doubling lasers

(1) fiber coupling diode end-pumped IR laser model

Under the steady-state condition and using the plane wave approximation, A formula relating the IR output power and diode pumped power have been derived by Mr.Paolo Laporta[3].The waist size of the TEM_{00} cavity mode determines the local power density and the beam divergence. Both parameters strongly influence the efficiency doubling.

$$P_{out}=\frac{T}{2g}h_p\frac{a(a+2)}{(1+a)^2}\left[P_{in}-P_{th}(a)\right] \qquad (1)$$

$$P_{th}=\frac{pgI_{sat}\bar{w}_p^2}{2h_p}(1+a) \qquad (2)$$

where $\eta_p = \eta_t \eta_a (h\nu / h\nu_p)$, η_t is the optical transfer efficiency (ratio between optical power incident on the active medium and that emitted by the pump source), η_a is the absorption efficiency (ratio between power absorbed in the active medium and that entering the rod). $h\nu_p$ is the energy of pump photon, $h\nu$ is the energy of laser photon; T is the power transmission of the output coupler; γ is the total logarithmic loss per pass(γ =T+ γ_i); γ_i is the intracavity loss per pass; $a = \frac{w}{\bar{w}_p^2}$, *w* is the waist of laser beam, $\bar{w}_p^2 = \left[\frac{1}{l} \int_0^{l^{\#}} w_p^2(z)\,dz \right]^{\frac{1}{2}}$ is the average of the spot size inside the active material, $l = \min \{ l, l^* \}$, *l* is the length of active medium, l^* is a suitable effective length related to the absorption length 1/a of the pump radiation and to the divergence angle θ_p of the pump beam inside the crystal. The assumption of $l=l^*$ does not give, in general, correct results. By numerical calculation, Paolo Laporta have found that, for $q_p \le 0.2$ rad, $l^* = (-2.3q_p + 1.8)(1/a)$, $w_p(z) = w_{p0} + \theta_p(z - z_0)$, W_{p0} is the radius at the waist and q_p is the far-field half-angle of the pump beam in the medium; $I_{sat} = \frac{hn}{st}$ is the saturation intensity, s is the cross section of the laser transition, τ is the upper energy state lifetime.

(2) Theoretical model for diode end pumped intra-cavity doubling frequency laser

Because the output mirror in intra-cavity frequency doubled laser is totally reflected at 1.06 micrometer wavelength and transmitted at the 0.53 micrometer wavelength, the second harmonic crystal in cavity acts as an output coupler in a manner analogous to the transmitting mirror of a normal laser. In the normal laser the transmitting mirror couples out power at the laser frequency, whereas the nonlinear crystal inside the laser couples out power at twice the laser frequency.

According to above illustration, the green laser power can be obtained by using frequency doubling efficiency (η_{SHG}) to replace the coupling mirror transmittance (T) in formula (1).

$$P_{SHG} = \frac{h_{SHG}}{2g} h_p \frac{a(a+2)}{(1+a)^2} [P_{in} - P_{th}(a)] \tag{3}$$

where $\gamma = \eta_{SHG}/2 + \gamma_i$;

$$P_{th} = \frac{p(g_i + h_{SHG}/2) I_{sat} \bar{w}_p^2}{2h_p} (1+a) \tag{4}$$

If Maxwell equations are solved for a coupled fundamental and second-harmonic wave propagating in a nonlinear medium, then the ratio of the power generated at the second-harmonic frequency to that incident at the fundamental is given by

$$h_{SHG} = \frac{P_{SHG}}{P_w} = \tanh^2 [lK^{1/2} (\frac{P_w}{A})^{1/2} (\frac{\sin l\Delta k/2}{l\Delta k/2})] \tag{5}$$

where $$K = 2h^3 w_1^2 d_{deff}^2 \tag{6}$$

l is the length of the nonlinear crystal, A is the area of the fundamental beam, η is the plane-wave impedance $h = \sqrt{m/ee_0} = 377/n_0$ [Ω], w_1 is the frequency of the fundamental beam, d_{eff} is the effective nonlinear coefficient of the crystal. The dimension of the d_{eff} in (6) is given in the MKS system and includes ε_0 , the permittivity of free space, thus d_{eff} [As/V^2]. Some authors exclude e_0 from the *d* coefficient, in this case *d* [As/V^2]=8.855×10^{-12}d [m/V]. The conversion from the cgs system to MKS unit becomes *d* [As/V^2] = 3.68×10^{-15}d [esu].

For low conversion efficiencies, (5) may be approximated by

$$h_{SHG} = \frac{P_{SHG}}{P_w} = l^2 K (\frac{P_w}{A})(\frac{\sin l\Delta k/2}{l\Delta k/2})^2 \tag{7}$$

The maximums SHG conversion efficient will be occur at idea phase-matched situation.

$$h_{SHG} = \frac{P_{SHG}}{P_w} = l^2 K \left(\frac{P_w}{A}\right) \qquad (8)$$

We can get intra-cavity power and SHG power from (8) at the phase matched situation.

$$P_w = \frac{h_{SHG} A}{l^2 K} \qquad (9)$$

$$P_{SHG} = \frac{h^2_{SHG} A}{l^2 K} \qquad (10)$$

Now the key problem is to get the frequency doubling efficient.
Dividing η_{SHG} at the two side in (3), one can get

$$P_w = \frac{1}{2(h_{SHG} + g_i)} h_p \frac{a(a+2)}{(1+a)^2} [P_{in} - P_{th}(a)] \qquad (11)$$

From (9) and (11), we can obtain a twice order equation about the η_{SHG} as following:

$$Bh^2_{SHG} + Ch_{SHG} - D = 0 \qquad (12)$$

where

$$B = \frac{A}{l^2 K};$$

$$C = \frac{g_i A}{l^2 K} + \frac{1}{4} \frac{a(a+2) p I_{sat} \bar{w}_p^2}{1+a}$$

$$D = h_p P_{in} \frac{a(a+2)}{(1+a)^2} - \frac{1}{4} \frac{a(a+2) p I_{sat} \bar{w}_p^2}{1+a} g_i$$

So from (12) the η_{SHG} can be obtained finally.

$$h_{SHG} = \frac{-C + \sqrt{C^2 + 4BD}}{2B} \qquad (13)$$

or

$$h_{SHG} = \frac{-C - \sqrt{C^2 + 4BD}}{2B} \qquad (14)$$

The η_{SHG} value of (14) is negative, so the solution should be neglected.

(3). Verifying the theory model by intra-cavity frequency doubling

In order to verify the theory model of diode end pumped intra-cavity frequency doubling, we use KTP crystal to get the experiments data of green power and use the equations (10) ---(13) to calculate the theoretical value of the green power.

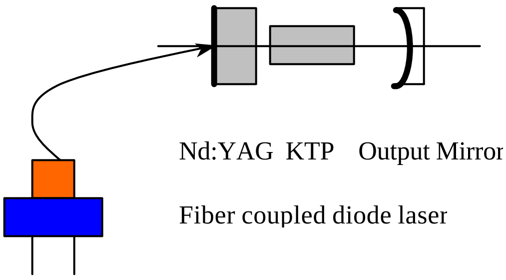

Fig. 1 The experimental setup of diode end pumped intra-cavity frequency doubled

The experimental setup is shown in Fig.1. A fiber coupled diode laser is used as the pumping source. The diameter of the fiber is 365 micrometers. The hemispherical laser resonator consists of one spherical output mirror (r=250mm) and one plane mirror, given by the Nd:YAG end surface. The Nd:YAG is 5mm diameter and 3mm longer. KTP is frequency doubled crystal. The size of KTP is 3mm×3mm×6mm.

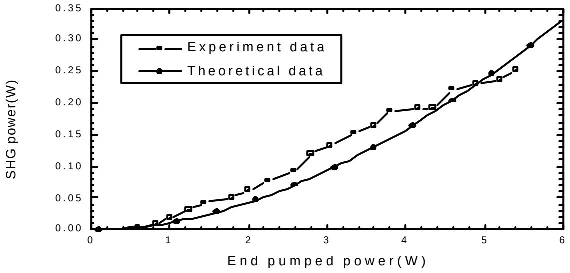

Fig.2 Diode pumping power Vs. Green laser power

Fig.2 shows the theoretical and experimental results of the intra-cavity doubling frequency. The diode end pumped intra-cavity doubling frequency theory model can well describe the experiment results by comparing the experiment and theoretical data.

3. Acknowlegement

I appreciate the DLR-IB for arranging such a successful visit and want to express my sincere thanks to Herrn T.Schierer and Frau Hongsernant for the invitation and financial support of BMBF by the DLR-IB and for effective help. I am grateful to professor Dr. Horst Weber at TU Berlin, professor Weilin Huang at HUST for the support of this cooperation and the intelligent advice from professor Weber on my research work. I want to thank Mr. Zhang qincheng, Dr. Ozygus, Dr. Laaps and all colleges in Prof. Weber's research group for their highly effective cooperation, sincere support and intelligent advice on my research work. I also want to thank Shandong University for their supporting the self doubling frequency crystals. Finally, I should give a special thank to my wife for her great supporting and taking care of our daughter.

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