# Continuous wave single longitudinal mode SHG with two stages of intra-cavity power enhancement at fundamental frequency

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### ABSTRACT

In common intra-cavity SHG schemes, the requirement for high(st) level of fundamental frequency power inside the non-linear crystal contradicts with the condition for extracting the maximum power available from the laser active medium. This impedance mismatch problem is removed by using the fundamental frequency power enhancement in two steps, the first one being optimized for maximum power outcoupling while at the second step the circulating inside nonlinear crystal power is further increased for maximum efficiency of SHG process. Experimentally proved this approach allows 3-5 times higher SH output power from DPSS lasers at given pump as compared with traditional schemes.

Keywords: DPSS Lasers, intra-cavity SHG, Nd:YVO<sub>4</sub>, continuous wave, single frequency, power enhancement

## **1. INTRODUCTION**

As the market demand for moderate power lasers in the green, blue and UV spectrum range spreads in direction of their industrial applications, the reliability and overall efficiency of laser sources become an economic issue. Traditional coverage of the above spectrum with gas (He:Cd, Argon ion) and frequency converted flash lamp pumped Nd:YAG lasers is now being replaced by frequency doubled and tripled DPSSL and by direct doubling of diode lasers <sup>(1)</sup>. The efficiency of frequency conversion process is strongly dependent on the power of fundamental frequency radiation interacting with a non-linear crystal, and for this reason an enhancement of interacting fundamental frequency power is required while dealing with continuous wave (cw) DPSS or diode lasers of low and moderate powers. The interacting power enhancement is commonly achieved either by using an external resonant cavity locked to the incident fundamental frequency or via intra-cavity frequency power is much higher of that outcoupled from the laser. Both above approaches have their inherent bottlenecks that affect the efficiency of laser system at combined frequency and require additional complexity for its stable and reliable performance. In the case of external resonant cavity the reflection from it back to the laser triggers unstable performance of the latter resulting in a noisy output from the system. To eliminate this undesirable feedback one have to use optical isolators, sometimes as complex as two stage Faraday isolators to provide isolation up to 60dB.

In common intra-cavity SHG schemes the condition for large enhancement of the fundamental frequency power inside the laser cavity is at variance with condition for maximum extraction of the power available from the laser at a particular level of pump supplied to the laser. This is a typical problem of matching inner and outer impedances for optimizing power extraction from a power source. For maximum output of the generated second harmonic power from the laser, the useful part of the cavity loss has to be of a certain (optimal) value that is dependent on the balance of total loss of the cavity and increases with increase of pump power. For effective interaction inside the non-linear crystal the power enhancement factor always needs to be high. This requires decreasing the cavity loss to a value as small as reasonable possible, which, however, results in the condition for outcoupling the laser power straying from its optimal value. Reviewing intra-cavity SHG in his book <sup>(2)</sup> W. Koechner summarises: "In most systems, the second-harmonic power is considerably below the output power which can be achieved at the fundamental wavelength. Insertion losses of the nonlinear crystal, or any other additional intra-cavity elements, are often the reason for the poor performance, or in the case of Nd:YAG, thermally induced depolarization losses can have a major effect. In low-gain lasers employed for intra-cavity harmonic generation, even small insertion losses are very detrimental to the system performance". The compromise for the maximal power output from the laser and large enhancement of the intra-cavity power for efficient

frequency doubling can be achieved within a narrow range of the laser regime parameters and, in particular, at the cavity total loss value being small, typically less than few %. This makes the traditional intra-cavity frequency conversion laser schemes highly sensitive to small external disturbances as these noticeably change the balance between outcoupling and internal cavity losses. As a result, special stabilization measures of laser set-up and tight tolerances on laser component's specification are needed for a stable and reliable laser performance.

To eliminate the above holdbacks it was suggested <sup>(3)</sup> a new concept for intra-cavity frequency conversion of laser radiation that is based on using a complex cavity capable of enhancing the fundamental frequency power interacting with the non-linear crystal in two steps, with the total enhancement factor being the product of the enhancement factors in each of them. This technique termed Double ENhanced Intra-CAvity Frequency Conversion (DENICAFC) allows both the condition for high enhancement of the interacting fundamental frequency power inside the nonlinear crystal and the condition for maximum power outcoupling from the laser to be satisfied simultaneously. Below we present the theoretical background for DENICAFC laser technology and experimental results of implementing it for efficient intra-cavity doubling of Nd:YVO<sub>4</sub> lasers.

## 2. DENICAFC LASER TECHNOLOGY: THEORETICAL MODEL

In fact the DENICAFC concept converts the main disadvantage of the external resonant cavity doubling technique, namely its undesirable feedback reflection, into well controllable and self adjustable outcoupling the fundamental frequency radiation power from the laser active medium, by making the external optical resonator with non-linear crystal inside as the functional part of the laser at fundamental frequency. This is illustrated by Fig. 1.



Fig. 1. a) Schematic layout of intra-cavity SHG implementing the DENICAFC technique. AC and NC stand for the laser active and doubling crystals accordingly. Mirrors R0, R1 and R2 make two parts of the complex laser cavity with intracavity coupler Rc between them. Mirrors R0, R1 and R2 are all highly reflective at the fundamental wavelength. The intra-cavity coupler Rc is partially reflective at fundamental wavelength but highly reflective at second harmonic. For unidirectional SH output mirror R2 is also highly reflective at the second harmonic wavelength while the mirror R1 is highly transmittive at it. b) The backward reflectivity of resonant reflector at two different values of intra-cavity coupling and internal losses. Other explanations are in the text.

In the above layout the complex cavity part made up of the mirrors R1, R2 and intra-cavity coupler Rc, but without the non-linear crystal in between, is known as Fox-Smith interferometer <sup>(4)</sup> that was initially suggested as a resonant frequency selector in <u>reflection</u> mode contrasting with Fabry-Perot etalon which resonates in transmission mode and, for preventing non-resonant reflection from it, needs to be tilted when is in use for selecting the frequency of a laser. The backward reflectivity  $R_{back}$  of Fox-Smith interferometer is a function of frequency which determines spectral position of the reflectivity peaks by the optical path  $L_2$  between mirrors R1 and R2 via classical standing wave cavity condition

$$L_2 = m\frac{\lambda}{2} \equiv m\frac{c}{2\omega} \quad , \tag{1}$$

with  $\lambda(\omega)$  being the wavelength (frequency) of the optical resonator eigenmode, c is the light velocity and m being an integer. The value of the reflectivity maxima of Fox-Smith interferometer is defined by the reflectivity values  $R_1$ ,  $R_2$  and  $R_c$  of corresponding mirrors:

$$R_{backM} = R_1 \cdot \frac{(1 - R_c)^2}{\left(1 - R_c \cdot \sqrt{R_1 \cdot R_2}\right)^2} \quad .$$
<sup>(2)</sup>

For a resonant cavity the capability of circulating power enhancement is due to the fact that not all the power incident upon the cavity is being lost in a single round trip (as a result of intra-cavity losses and output from the cavity); certain amounts of the power remain in the cavity after each single round trip and, when added to each other in phase, build up the intra-cavity circulating power much higher that the incident one. Hence, at resonance reflection the value of circulating intra-cavity power inside the Fox-Smith interferometer part of the above complex cavity is manifold increased as compared with the power value incident upon it from the first part of the cavity that incorporates the active laser medium. This second stage of intra-cavity power enhancement provides the opportunity for efficient intra-cavity frequency conversion while keeping the power outcoupled from the active laser medium at maximum.

Placing the non-linear crystal inside the Fox-Smith interferometer part of the complex laser cavity makes this part of the cavity <u>a non-linear resonant reflector</u> whose reflectivity peak values become dependent also on the non-linear loss corresponding to the fundamental frequency power depletion due to the frequency conversion process. One can show that for the geometry of Fig. 1 the fundamental frequency power enhancement factor  $E_{NLR}$  inside the non-linear crystal at resonance can be written as

$$E_{NLR}(P_{\omega},R_{c}) = \frac{R_{c}R_{1}(1-R_{c})T_{nc}\exp\left[-\left(\frac{\alpha L_{nc}+\beta P_{\omega}}{2}\right)\right]}{\left(1-R_{c}T_{c}^{2}\sqrt{R_{1}R_{2}}\exp\left[-\left(\alpha L_{nc}+\beta P_{\omega}\right)\right]\right)^{2}} \cdot \left\langle1+R_{2}T_{nc}^{2}\exp\left[-\left(\alpha L_{nc}+\beta P_{\omega}\right)\right]\right\rangle, \quad (3)$$

and the maximum reflectivity value of the resonant reflector part of the complex cavity is given as

$$R_{backM}(P_{\omega}, R_{c}) = \frac{R_{1}(1 - R_{c})^{2}}{\left\langle 1 - R_{c}T_{nc}^{2}\sqrt{R_{1}R_{2}}\exp[-(\alpha L_{nc} + \beta P_{\omega})] \right\rangle^{2}}.$$
(4)

In the above formulae  $L_{nc}$ ,  $\alpha$  and  $T_{nc}$  represent the non-linear crystal length, background loss and its surface's transmission, accordingly.  $P_{\omega}$  stands for the value of circulating fundamental frequency power inside the non-linear crystal and  $\beta$  is the coefficient of fundamental frequency power conversion,  $P_{2\omega} = \beta P_{\omega}^2$  with  $P_{2\omega}$  being the power of second harmonic. In the approximation of low power depletion, i.e.  $\beta P_{\omega} \ll 1$ , and negligible walk-off between the fundamental frequency and second harmonic beams inside the non-linear crystal, the power conversion coefficient can be taken <sup>(5)</sup> as

$$\beta = \frac{8\pi^2 D_{eff}^2 L_{nc}^2}{\varepsilon_0 n_{\omega}^2 n_{2\omega} c \lambda_{\omega}^2 w_0^2},$$
(5)

where  $D_{eff}$ ,  $n_{\omega}$  and  $n_{2\omega}$  are the effective non-linear optical coefficient and refractive indexes of the crystal at the fundamental and second harmonic wavelengths,  $\mathcal{E}_0$  is the dielectric constant, and  $w_0$  stands for the Gaussian radius of the interacting fundamental frequency beam.

Obviously  $R_{backM}$  is the reflectivity of the second (resonant) part of the complex laser cavity as it is seen from its first part and, when the threshold of lasing is reached, effectively stands for the fundamental frequency output coupler reflectivity, if one is interested of what power at the fundamental frequency is available outside the first part of the complex cavity. The fundamental frequency output power available from the laser with outcoupler reflectivity  $R_{backM}$  can be written then as

$$P_{\omega OUT}(P_{\omega}, R_{c}) = S_{ac}I_{s} \frac{\ln\left(\frac{1}{R_{backM}(P_{\omega}, R_{c})}\right)}{2} \cdot \left[\frac{2g_{0}L_{ac}}{\ln\left(\frac{1}{R_{backM}(P_{\omega}, R_{c})}\right) + \theta} - 1\right].$$
(6)

The above formula (6) is valid for the lasers employing active crystals with four-level energy scheme <sup>(2)</sup>.  $S_{ac}$  is the cross-sectional area of the laser beam inside the active crystal  $L_{ac}$  long;  $I_s$  and  $g_0$  are the saturation intensity and unsaturated gain.  $\theta$  represents internal (useless) cavity losses that also include fundamental frequency power leaking through the mirrors R0, R1 and R2 and loss at active crystal end surfaces. In the case of linear outcoupler, for the maximum output power the optimized value of outcoupling  $(1 - R_{back})$  depends on the unsaturated gain available in the laser active medium and on the internal round trip losses of the cavity. However, for our case of the non-linear resonant reflector the outcoupling value  $(1 - R_{back} (P_{\omega}, R_c))$  depends, in its own turn, on the fundamental frequency power  $P_{\omega}$  circulating inside the resonant reflector and, hence, for the optimization of second harmonic output one has to resolve the equation (6) taking into account dependencies (3) and (4). These all relate to each other as

$$P_{\omega} = \frac{P_{\omega OUT}(P_{\omega}, R_c)}{1 - R_{backM}(P_{\omega}, R_c)} \cdot E_{NLR}(P_{\omega}, R_c).$$
(7)

One has to note, that  $\frac{P_{\omega OUT}(P_{\omega}, R_c)}{1 - R_{backM}(P_{\omega}, R_c)}$  is the fundamental frequency power incident upon the resonant non-linear

reflector from the first part of the complex DENICAFC cavity, from the direction of the laser active medium, and

$$E_{1ST} = \frac{1}{1 - R_{backM}(P_{\omega}, R_c)}$$
(8)

is the enhancement factor at the first stage of intra-cavity power enhancing.

### 3. DENICAFC ND: YVO4/KTP LASER PERFORMANCE SIMULATION

Based on the above theoretical model in the following we present the results for the DENICAFC Nd:YVO4 laser frequency doubled with KTP crystal. For simulation of the laser performance it is assumed that all the pump power from

1.5W laser diode at 808.5nm is absorbed by the Nd-doped ortho-vanadate crystal of length  $L_{ac} = 3$ mm within the absorbing volume perfectly overlapped with the laser cavity TEM<sub>00</sub> transverse mode of Gaussian radius  $w_0 = 0.09$ mm. In calculations cavity mirror's reflectivity at fundamental wavelength  $R_0 = R_1 = R_2 = 0.998$ . KTP crystal length  $L_{nc} = 5$ mm and its effective non-linear optical coefficient  $D_{eff} = 3.56 \cdot 10^{-12}$  m/V. The fundamental and the second harmonic variables  $\frac{\lambda}{2}$  and  $\frac{\lambda}{2}$  are 1064nm and 522nm accordingly. The calculated laser permeters are presented in

wavelengths  $\lambda_{\omega}$  and  $\lambda_{2\omega}$  are 1064nm and 532nm accordingly. The calculated laser parameters are presented in following graphs. As one sees from Fig. 2 the second harmonic output power from the laser hits its maximum at the intra-cavity coupler reflectivity value close to 0.9, showing throughput efficiency (optical output to optical pump power)



Fig. 2. SH output power (W) as function of intra-cavity coupler reflectivity from DENICAFC Nd:YVO4/KTP laser pumped with 1.5W at 808nm. The internal (useless) cavity loss value is assumed 1% per cavity round trip.

over 40%. It is also seen that the SH output dependence on intra-cavity coupler reflectivity value is relatively shallow due to an interesting feature of the non-linear resonant reflector that self regulates (as a consequence of nonlinearity) the value of  $R_{backM}$  to be close to the optimal value for outcoupling the fundamental frequency power from the first part of the complex DENICAFC cavity. Fig. 3 illustrates this feature of the non-linear resonant reflector showing almost no dependence of  $R_{backM}$  on the parasitic loss in the laser cavity. This explains low sensitivity of the DENICAFC laser to external influences, alignment and component's specification tolerances.



Fig. 3. Backward reflectivity of the non-linear resonant reflector via the reflectivity of the intra-cavity coupler at the cavity internal loss values 0.5% and 5%.

The fundamental frequency enhancement factors are presented in Fig. 4. One can see that despite the enhancement factors at each of two steps of enhancement vary with the change of intra-cavity coupler reflectivity, the total

enhancement remains almost constant, giving the reason for shallow dependence of the SH output on intra-cavity coupler reflectivity.



Fig. 4. Enhancement of the fundamental frequency circulating intra-cavity power via intra-cavity coupler reflectivity. The internal cavity loss value is assumed 1%.

The graphs in Fig. 5 compare DENICAFC laser technology with traditional intra-cavity doubling. The calculation for traditional doubling is presented for case of unidirectional SH output from the folded laser cavity. All parameters for the active and nonlinear crystals, cavity modes and pumping are identical. Assuming the same reason for inserted cavity loss, one can see a significant difference in output power stability for two technologies. One can see that at the cavity loss value within 2% to 10% the SH output power from DENICAFC laser is 3-5 times higher of that from a traditional intra-cavity doubling scheme.



Fig. 5. Dependence of second harmonic output power from DENICAFC ( $P_{2\omega}$ ) and traditional intra-cavity doubled ( $P_{2\omega C}$ ) lasers on the cavity internal loss. For the DENICAFC case intra-cavity coupler reflectivity is taken close to its optimal value  $R_c = 0.9$ . Output power, in W, is shown for the case of absorbed pump power 1.5W.

## 4. CONCLUSION

The experimental results on DENICAFC laser technology for frequency doubling have been implemented in development of commercial lasers by KLASTECH GmbH. To utilise on spectral selectivity of the non-linear resonant reflector one of the cavity mirrors (R1 or R2) has to be piezo-controlled for longitudinal mode matching between two parts of the complex DENICAFC cavity. For this purpose the leaking power either through mirror R2 or intra-cavity coupler Rc can serve as feedback signals. Once the two cavity parts of the DENICAFC cavity locked on one of the cavity longitudinal modes, the output from the laser is of single frequency with coherent length over 100m. A typical

experimental spectrum of DENICAFC laser is shown in Fig. 6. When the cavity is locked the overall laser efficiency, from pump power to 532nm output, is typically over 25% with cw output power stability better than 1% over 8 hours.



Fig. 6. Experimental spectrum of 532nm output from DENICAFC laser, taken by Coherent's optical spectro-analyzer with 1.5GHz FSR. Resolution of the spectral linewidth is limited by digitization of the signal from the spectro-analyzer and its finesse. The rectangular signal indicates the scanning range of the spectro-analyzer that is about 150% of its FSR.

Thus, it is shown theoretically and experimentally that implementation of two steps of the power enhancement in intracavity frequency doubling allows magnificent increase of the laser overall efficiency, allowing high second harmonic output power at relatively low pump.

#### REFERENCES

- <sup>1</sup> W. P. Risk, T. R. Gosnell and A.V. Nurmikko, *Compact Blue-Green Lasers*, Cambridge University Press, 2003
- <sup>2</sup> W. Koechner, *Solid-State Laser Engineering*, Third Edition, Springer-Verlag Berlin Heidelberg, 1992.
- <sup>3</sup> F. Karpushko, *Intracavity Frequency Conversion of Laser Radiation*, Patent specification, EPO No 1 442 507.
- <sup>4</sup> P.W. Smith, "Mode Selection in Lasers", Proc. IEEE, **60**, 422-440 (1972).
- <sup>5</sup> R. L. Sutherland, *Handbook on Nonlinear Optics*, Marcel Dekker, 1996.