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Modeling of wavelength-selectable visible Raman lasers

David J. Spence *, Xiaoli Li, Andrew J. Lee, Helen M. Pask

MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, NSW 2087, Australia

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We derive a numerical model of visible Raman lasers that employ simultaneous intracavity Raman shifting and intracavity second-harmonic or sum-frequency generation. We show excellent agreement with previous experimental results, and explain the mechanism by which sum-frequency generation can inhibit the generation of the Stokes field. We predict that increased output powers should be achieved using unusually short crystals of only few millimeters length.

1. Introduction

Frequency conversion of lasers has resulted in wide coverage of the ultraviolet, visible and infrared spectral regions with just a limited number of common laser materials such as Ti:Sapphire and Nd^{3+}-doped materials such as Nd:YAG. Frequency-doubling and mixing using $\chi^{(2)}$ non-linear crystals allow simple conversion of each laser's fundamental wavelength to several others. Combining these processes with $\chi^{(3)}$ stimulated Raman scattering (SRS) has been shown to extend the wavelength coverage available from common lasers, and can target spectral gaps that are otherwise hard to reach [1–3]. Most explored is the conversion of Nd-doped lasers, and with simple changes to the robust and well-tested architecture of those lasers, tens of new wavelengths have been generated [3]. There has been particular focus on lasers operating in the yellow-to-red spectrum, relying on simultaneous intracavity Raman shifting and frequency doubling of a fundamental laser, which can operate efficiently even as continuous-wave lasers [4,5]. Lasers with wavelength-selectable output can be realized by using the doubling crystal to select which of the multiple intracavity fields to combine and couple out of the cavity. We have successfully demonstrated efficient lasers that can generate two or more visible wavelengths at multiwatt output power levels [6] and using modest few Watt diode pump sources [7].

While the architecture of these lasers is very simple and the components are all extremely robust, the challenge lies in understanding their behavior: Lasing at the fundamental wavelength and the simultaneous $\chi^{(3)}$ and $\chi^{(2)}$ processes in the cavity have complex interdependencies, and there are many variables to be considered to achieve the best efficiency for the desired mode of operation. Our most recent results [7] have showed some unexpected behaviors that we interpreted to be caused by excess $\chi^{(2)}$ non-linearity inhibiting the Raman process. In this paper, we present a numerical model for visible intracavity Raman lasers, building upon our previous model [8] to include sum-frequency mixing and a more informed interpretation of resonator loss. We use the results to confirm our interpretation of previous experimental results, and to make predictions for optimizing lasers of this type.

2. Description of model

We first describe the general laser design that we will model. The linear two-mirror cavity contains a laser material, a Raman-active material, and a $\chi^{(2)}$ material for frequency mixing. In many lasers, a single "self-Raman" crystal acts both as laser gain and Raman material, but the model is presented for the more general case. The laser material is longitudinally pumped through an end mirror designed for high transmission at the pump wavelength. The laser crystal generates a fundamental field inside the cavity, and this intracavity fundamental field is Raman shifted to generate a first Stokes field; the cavity mirrors are designed to be highly reflective for both of these fields. Power is coupled out of the cavity by the frequency mixing crystal—this crystal is temperature tuned to select between second harmonic generation (SHG) of the fundamental field, SHG of the Stokes field, and sum-frequency mixing (SFM) of the two fields. The visible output exits through the end mirror with high transmission. A second visible beam is generated in the other direction; that beam in principle could be extracted using an intracavity mirror that is not used in this present work. We have previously reported modeling of an intracavity Raman laser system [8] with intracavity SHG; in this work we extend that model to include the SFM process, and show

* Corresponding author.
E-mail address: david.spence@mq.edu.au (D.J. Spence).

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that very different dynamics can develop as a consequence. A related model considering SFM in an externally-pumped Raman oscillator was presented by Koch and Moore [9].

We present below a set of rate equations that can be used to model the behavior of the laser.

$$\frac{dN^*}{dt} = \frac{P_P\lambda_P}{hc} - \frac{N^*}{\tau_L} - \frac{2\sigma_L N^* P_F}{A_L}\frac{\lambda_F}{hc} \tag{1}$$

$$\tau_{RT}\frac{dP_F}{dt} = -P_F L_F + \frac{2\sigma_L N^* P_F}{A_L} - \frac{4P_F P_S g_R l_R}{A_R \eta} - 2\frac{(2m-1)}{m}\frac{\gamma_{\mathrm{GREEN}} P_F^2}{A_D} - 2\frac{4}{1+\eta}\frac{\gamma_{\mathrm{LIME}} P_F P_S}{A_D} \tag{2}$$

$$\tau_{RT}\frac{dP_S}{dt} = -P_S L_S + \frac{4 g_R l_R P_F P_S}{A_R} - 2\frac{(2m-1)}{m}\frac{\gamma_{\mathrm{YELLOW}} P_S^2}{A_D} - 2\frac{4\eta}{1+\eta}\frac{\gamma_{\mathrm{LIME}} P_F P_S}{A_D} \tag{3}$$

The equations describe the time rate of change of N^*,P_F, and P_S, where N^* is the total number of inverted ions, and P_F,P_S are fundamental and Stokes one-way intracavity powers. In the laser-, Raman-, and doubling-crystals respectively: A_L, A_R and A_D are the spot areas (with corresponding spot radii r_L, r_R and r_D), l_L, l_R and l_D are the crystal lengths, and n_L, n_R and n_D are the crystal refractive indices (assumed equal at all wavelengths). L_F and L_S are the round-trip losses for the fundamental and Stokes fields (including mirror transmissions). The cavity round trip time is $\tau_{RT}=2l/c$, in which the cavity optical length $l=[l_C+l_L(n_L-1)+l_R(n_R-1)+l_D(n_D-1)]$, where l_C the physical cavity length. With these definitions, we note that $\tau_{RT}P$ is then the intracavity energy stored in each field. σ_L and τ_L are the laser crystal emission cross section and upper-level lifetime, g_R is the stimulated Raman gain coefficient, P_P is the absorbed diode pump power, λ_P, λ_F and λ_S are the wavelengths of the pump, fundamental, Stokes radiation, and $\eta=\lambda_F/\lambda_S$. Three 'output coupling' routes are included: SHG of P_F to generate green, SFM of P_F and P_S to generate lime, and SHG of P_S to generate yellow. The parameters γ_{GREEN}, γ_{LIME}, and γ_{YELLOW} describe strength of these three $\chi^{(2)}$processes, calculated to be [10]

$$\gamma_{\mathrm{OUT}} = \frac{2\pi^2 d_{eff}^2 l_D^2}{\varepsilon_0 c n^3 \lambda_{\mathrm{OUT}}^2}\,\mathrm{sinc}^2\left[\pi(t-t_{\mathrm{OUT}}^{\mathrm{PM}})l_D/\Delta t_{\mathrm{OUT}}^{\mathrm{PM}}\right] \tag{4}$$

in which the 'OUT' subscripts should be replaced throughout by one of 'GREEN', 'LIME' and 'YELLOW'. d_{eff} is the effective non-linearity of the doubling crystal, and λ_{OUT} is the generated wavelength. These γ parameters include the temperature dependence of the conversion efficiency for each output wavelength in the sinc^2 term, where t is the crystal temperature, $t_{\mathrm{OUT}}^{\mathrm{PM}}$ is the phase matching temperature, and $\Delta t_{\mathrm{OUT}}^{\mathrm{PM}}$ is the temperature acceptance bandwidth (defined as the range over which $l_D\Delta k$ ranges from $-\pi$ to π [11], where Δk is the wavevector mismatch between the infrared and generated visible fields). For most temperatures, just one of these processes will dominate. Finally we can deduce the output powers in the visible as [10–13]

$$P_{\mathrm{GREEN}}^{\mathrm{out}} = \frac{(2m-1)}{m}\frac{\gamma_{\mathrm{GREEN}} P_F^2 T_{\mathrm{GREEN}}}{A_D} \tag{5}$$

$$P_{\mathrm{LIME}}^{\mathrm{out}} = \frac{4\gamma_{\mathrm{LIME}} P_S P_F T_{\mathrm{LIME}}}{A_D} \tag{6}$$

$$P_{YELLOW}^{out} = \frac{(2m-1)}{m}\frac{\gamma_{\mathrm{YELLOW}} P_S^2 T_{\mathrm{YELLOW}}}{A_D} \tag{7}$$

where T_{GREEN}, T_{LIME}, and T_{YELLOW} are the output coupler transmissions at each visible wavelength, and m is the number of longitudinal modes oscillating in the relevant infrared field.

By setting Eqs. (1–3) to zero and solving, we find the steady-state values of all variables appropriate for stable CW lasing. Key points to note are as follows: the SHG coefficients have a factor $(2m-1)/m$ that accounts for up to a factor of two enhancement of the doubling due to mode beating of m longitudinal modes [13], and the extra factor 4 for SFM accounts for the increased non-linearity compared to the SHG process [12]. For SFM, the power coupled out of the cavity is depleted unevenly from the fundamental and Stokes fields in the ratio of the photon energies. Both forward- and backwards-SRS are included, and both have equal strength in this regime where the dispersion between the fundamental and Stokes fields is large over the characteristic length for Raman gain [14,15]. Note that backwards-SRS was omitted in the model in [8].

The model is generic and could be applied to any intracavity Raman laser with intracavity frequency mixing, not just the miniature lasers discussed below. We briefly discuss here the caveats that should be considered before applying the model more generally. The equations are framed in terms of beam power, and include a factor from an overlap integral that arises when the intensity rate equations are integrated over the transverse intensity distributions. For example, the Raman process, which is proportional to $I_F(r)I_S(r)$, leads to a term $\xi P_F P_S$, where ξ is the normalized overlap integral $\int I_S(r)I_F(r)dA/(\int I_S(r)dA \times \int I_F(r)dA)$; a similarly defined factor ξ is also appropriate for the laser gain and $\chi^{(2)}$ terms. Our equations assume matched Gaussian transverse profiles with $1/e^2$ radius r, for which ξ has the value of $1/\pi r^2$, resulting in the $1/A$ factor in all lasing, Raman and $\chi^{(2)}$ terms.

A second assumption is that the mode sizes are constant throughout each individual crystal (although the sizes can be different in the different crystals). For lasers in which this cannot be assumed, we should use Boyd and Kleinman coefficients [12] for the $\chi^{(2)}$ process and suitably averaged spot sizes in the Raman and laser crystals. Finally, we assume that the fundamental spectral width is narrow compared to the spontaneous Raman linewidth, and that the all fields are spectrally narrow compared to the tolerance of the $\chi^{(2)}$ processes.

For lower power lasers [7] that we address below, these approximations are valid. For multiwatt lasers of this type [6] however, the transverse profiles do actually depart substantially from Gaussian, with the result that the effective strengths of the $\chi^{(2)}$ and Raman processes are reduced [16]. The spectrum can also become broadened at higher powers, resulting in a reduction in the effective Raman cross-section. Both these effects are beyond the scope of the current model, but generally may cause a decrease in experimental efficiency and output power as they arise.

3. Analysis of a miniature Raman laser

We have previously studied experimentally [7] a miniature embodiment of a Raman laser with intracavity frequency conversion such as is described by the model. In the remainder of this paper, we will model a laser based on that work, comparing the predictions of the model to data from that work; we will use the model to illustrate the physics of this complex laser system, and make predictions of the optimum configurations of such a laser.

The parameters for this laser are listed in Table 1; we briefly summarize key data from [7] since they underpin the analysis presented in the present work. The experimental work used a 3 mm long Nd:YVO_4 self-Raman crystal, and either a 5 mm or 10 mm long LBO crystal, pumped by up to 3.8 W of diode power at 808 nm [7]. Lasing at 1064 nm and generating an intracavity Stokes field at 1176 nm, the laser could be configured either to double the Stokes field to output a 588 nm yellow wavelength, or to sum-frequency-mix the fundamental and Stokes fields to output a 559 nm lime wavelength. The output wavelength could be selected simply by changing the temperature of the LBO crystal