Numerical simulation of the magnetically gain-switched chemical oxygen-iodine laser

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ABSTRACT

During the operation of the magnetically gain-switched chemical oxygen-iodine laser (MGS-COIL), the transition intensity of hyperfine transition line 2-2 can exceed that of line 3-4, which is the dominant line at zero magnetic field. For this reason, a simulation model including both 3-4 and 2-2 transition lines is necessary to describe the mode buildup process in MGS-COIL. In this paper, we assume that 3-4 and 2-2 transition lines simultaneously oscillate in laser cavity. The propagation of optical field is calculated based on FFT. The required frequency, rise time and residual field of the magnetic gain-switch for a high-performance MGS-COIL are analyzed based on simulation results.

1. Introduction

Owing to its power scalability, short wavelength, atmospheric transmittance and excellent beam quality, the chemical oxygen iodine laser (COIL) is a competitive high-power laser for both industrial and military applications [1]. During the past decades, great achievements have been made on the development of COIL operating in continuous wave mode. However, some studies have shown that a pulsed COIL may be necessary or more efficient for certain applications, such as metal processing [2] and nonlinear frequency conversion [3]. Compared to the success of cw COIL, the performance of pulsed COIL remains not up to the requirements of the above-mentioned applications [4].

The main difficulty to transform a cw COIL directly into a repetitively pulsed one is to obtain an ideal Q-switch or gain-switch element, which has large clear diameter (>5 cm), high capable average power (>1 kW), and meanwhile high repetition frequency (>1 kHz). Currently, optical switches based on electro-optic or the acousto-optic effect cannot meet these requirements simultaneously [5]. Magnetic gain switch [6] is an attractive solution which avoids these problems by applying a pulsed magnetic field to laser cavity rather than inserting any optical elements. Nevertheless, the cost of a device that generates the pulsed magnetic field required for magnetic gain switch is very high so very few MGS-COIL experiments have been reported. Two of them were the GS-I test [7] and the GS-II test [8]. In both two tests, magnetic gain switch was achieved by the fast magnetic field nulling technique. Two arrays of permanent magnets were located above and below the laser cavity to create a uniform static magnetic field of approximately 400 Gauss. The gain of atomic iodine was suppressed below lasing threshold conditions, so no output produced. Then the field coils located between the permanent magnets and laser cavity were rapidly charged, which immediately generated a uniform magnetic field opposite to the static field. Those two magnetic fields cancelled each other, so gain of COIL recovered and a lasing pulse was produced. The results of both two tests were analyzed by a one-dimensional simplified theoretical model described in [7]. Longitudinal mode competition was neglected in this model. However, dual-line lasing has been observed in [9] when magnetic field increased from 0 to 400 Gauss. Thus, considering only one transition line, which is common in the case of cw COIL, is not exact to describe the mode buildup process in MGS-COIL, especially when the magnetic gain-switch speed is low. In previous works, effects of some parameters of the magnetic gain switch on laser performance were not analyzed. Since the cost of a pulsed magnetic field generator used in the MGS-COIL is very high, it is necessary to determine the basic requirements of the pulsed magnetic field in order to minimize the cost and technical difficulties.

In this paper, a numerical model which consists of a one-dimensional pre-mixed flow field, a two-dimensional optical field and a two-dimensional magnetic field is established to predict the performance of a MGS-COIL. The transition cross section of 127I in the presence of an external magnetic field is theoretical calculated based on perturbation theory. The propagation of optical field is calculated by the angular
spectrum method based on FFT. During the simulation, the two strongest transition lines, line 3–4 and line 2–2, simultaneously oscillate in laser cavity. A kinetic model including quenching of I*, optical extraction, oxygen-iodine energy transfer and hyperfine relaxation is adopted to describe the dynamic process in laser cavity. In order to reduce the computational burden, these processes are divided into two groups: a “fast” group and a “slow” group. Effects of different parameters of the magnetic gain switch on laser performance are discussed based on computation results and the basic requirements of the magnetic gain switch are determined.

2. Numerical methods

2.1. Zeeman spectra of atomic iodine

The operation principle of a MGS-COIL is based on the Zeeman effect in atomic iodine. The hyperfine energy level structure of $^{127}$I is shown in Figure 1(a). A theoretical model describing the Zeeman spectra of the $^2\text{P}_{3/2} \rightarrow ^2\text{P}_{1/2}$ transition has been presented in [10]. According to this model, the gain on a transition between a state $i$ of the upper level and a state $j$ of the lower level is expressed as

$$g_{q}^i(\nu) = \frac{a_{q}^i}{8\pi k_{ij}} f_{ij}(\nu) \left( N_i - N_j \right)$$

$$= \sigma_{q}^i(\nu) \left( N_i - N_j \right),$$

(1)

where $k_{ij}$ is the wavenumber of the transition $i \rightarrow j$, $h$ is Planck’s constant, $f_{ij}(\nu)$ is the Voigt line shape function, $N_i$ and $N_j$ are the particle densities of state $i$ and $j$, respectively. The $a_{q}^i$ is transition probability rate, given by

$$a_{q}^i = \frac{64\pi^2 k_{ij}^3}{3\hbar^2} | \langle \psi_j | \hat{P}_q | \psi_i \rangle |^2,$$

(2)

where $\hat{P}_q$ is the $q$th component of the magnetic dipole moment operator, $\psi_i$ and $\psi_j$ are the quantum state functions of state $i$ and $j$, respectively. The values of $k_{ij}$, $\psi_i$ and $\psi_j$ depend on the strength of magnetic field and can be determined by diagonalizing the matrix of perturbation Hamiltonian $H'$, which consists of hyperfine interaction and Zeeman interaction. When there is no magnetic field, only six transitions are allowed due to the selection rule $\Delta F = 1$. In this paper, a computer program was developed to calculate the Zeeman spectra based on the theoretical model described above. The calculated normalized transition spectrum of $^{127}$I at zero field is shown in Figure 1(b).

The small signal gain of line $F' \rightarrow F$ is obtained by summing over all transitions between state $i$ of the upper level $F'$ and a state $j$ of the lower level $F$, given by,

$$g_{F', F}^i(\nu) = \sum_{ij} \sigma_{q}^i(\nu) \left( N_i - N_j \right)$$

$$= \sum_{ij} \sigma_{q}^i(\nu) \left( N_i - N_j \right)$$

$$= \sigma_{F', F}^i(\nu) \Delta N_{F', F},$$

(3)

where $\Delta N_{F', F}$ is the difference in population between states $F'$ and $F$.

Figure 1. (a) Hyperfine structure and allowed magnetic dipole transitions of $^{127}$I at zero field; (b) Theoretical transition spectrum at zero field; (c) and (d) are gain suppression curves for p- and s-polarized light, respectively. The green line represents the maximums of the other transition lines. The line broadening parameters are: 200 K, 10 Torr, 4.2 MHz/Torr.
where $N_F$ and $N_P$ are the particle densities of upper level $F$ and lower level $P$, $g_F$ and $g_P$ are the degeneracy of hyperfine level $F$ and $P$ in upper level $^2P_{1/2}$ and lower level $^2P_{3/2}$, respectively.

The polarization of the qth component of magnetic dipole radiation depends on the orientation of the magnetic field to the laser axis. When the magnetic field is perpendicular to the laser axis, the electric field vector of the radiation is linearly polarized perpendicular ($p$-polarized) and parallel ($s$-polarized) to the magnetic field for $q = \Delta M = 0$ and for $q = \Delta M = \pm 1$, respectively. The gain suppression curves are calculated by Eqs. (1), (2), and (3) and shown in Figure 1(c) and (d). Apparently, $s$-polarized light is easier to be suppressed, so usually a Brewster window is used to polarize the laser to be parallel to the magnetic field.

### 2.2. Propagation of optical field

For optical field propagation in cavity of MGS-COIL, only geometrical optics models have been applied in previous works. The Fabry-Perot model was adopted in [7] and the rooftop model was adopted in [8] to include the influence of upstream-downstream optical coupling effect. To preserve the geometry of cavity as much as possible, wave optics models must be adopted. Therefore, we developed a two-dimensional Fox-Li type iterative simulation model based on Sziklas and Siegman's idea [11]. The gain medium is divided into 5 axial segments and each segment is simplified to a gain sheet as shown in Figure 2.

The free propagation between each two gain sheets is calculated by angular spectrum method, which can be implemented by FFT method:

$$u(x, y, z = z_0 + d) =$$

$$\text{IFFT}\left\{\text{FFT}[u(x, y, z = z_0)] \cdot \exp\left\{2\pi i \left(\frac{d}{\lambda} \sqrt{1 - (\mathbf{k}_x)^2 - (\mathbf{k}_y)^2}\right)\right\}\right\},$$

(4)

where $d$ is the distance between two gain sheets, $\lambda$ is wavelength and $\mathbf{k}_{x,y}$ are spatial frequencies. Then the amplified optical field through the gain sheet is express by

$$u'(x, y) = \exp\left\{\frac{1}{2} \text{g}(x, y) d\right\} u(x, y)$$

(5)

where $g(x, y)$ is the total gain distribution contributed by the gain medium within one segment.

In addition, a random noisy input field is necessary when apply this iterative propagation method to stable resonators with high Fresnel numbers [12, 13]. Assuming the amplitude of a input field is $u_0(x, y)$, the random noise is added in following form:

$$u_i(x, y) = u_0(x, y) \exp\{2\pi i \text{rand}(x, y) - 1/2\},$$

(6)

where rand $(x, y)$ is a random number in the range 0–1 generated by computer programs, $u_0(x, y)$ is the initial field produced by spontaneous radiation of excited atomic iodine.

### 2.3. Kinetics model

The computation of flow field is simplified by using a one-dimensional premixed flow model described in [14]. The temperature, gas density, and flow velocity are assumed constant and the dissociation of iodine is assumed to be completed before the gas flows into laser cavity. To describe the competition between line 3 and line 2-2, a relaxation model similar to [15] is used to describe the hyperfine relaxation process of atomic iodine. The whole kinetic model adopted in this paper is summarized in Table 1. All rate constants can be found in [14, 15].

To prevent the step size of gas flowing along x-axis is too small, all processes are divided into two groups: a “fast” group and a “slow” group. The processes in “fast” group are computed every time light propagates between two gain sheets along z-axis, including optical extraction, oxygen-iodine energy transfer and hyperfine relaxation. The processes in “slow” group are computed every time gas flows, including quenching by residual molecular iodine and water vapor. In our simulation, the gas flows once for every 8 round trips of light in the cavity.

The rate equations in “fast” group can be express as following:

$$\frac{d}{dt} \left[\sum \right] = \left[ k_v [\Delta|t|] - k_r \left[ \sum \right] \right]$$

$$\frac{d}{dt} [\Delta] = k_v \left[ \sum \right] - k_r [\Delta|t|]$$

$$\frac{d}{dt} |t'\rangle_3 = \frac{7}{12} k_v [\Delta|t|] - k_r \left[ \sum |t'\rangle_3 - Q_e \left( |t'\rangle_3 - \frac{7}{12} |t| \right) \right]$$

$$- g_{s,1}(B) |n_{s,1}|^2$$

$$\frac{d}{dt} |t'\rangle_2 = \frac{5}{12} k_v [\Delta|t|] - k_r \left[ \sum |t'\rangle_2 - Q_e \left( |t'\rangle_2 - \frac{5}{12} |t| \right) \right]$$

$$- g_{s,2}(B) |n_{s,2}|^2$$

$$\frac{d}{dt} |t'\rangle_4 = \frac{9}{24} k_v [\Delta|t|] - k_r \left[ \sum |t'\rangle_4 - Q_e \left( |t'\rangle_4 - \frac{9}{24} |t| \right) \right]$$

$$+ g_{s,1}(B) |n_{s,1}|^2$$

(7)

$$\frac{d}{dt} |t\rangle_5 = \frac{7}{24} k_v [\Delta|t|] - k_r \left[ \sum |t\rangle_5 - Q_e \left( |t\rangle_5 - \frac{7}{24} |t| \right) \right]$$

$$+ g_{s,1}(B) |n_{s,1}|^2$$

$$\frac{d}{dt} |t\rangle_6 = \frac{5}{24} k_v [\Delta|t|] - k_r \left[ \sum |t\rangle_6 - Q_e \left( |t\rangle_6 - \frac{5}{24} |t| \right) \right]$$

$$+ g_{s,2}(B) |n_{s,2}|^2$$

$$\frac{d}{dt} |t\rangle_7 = \frac{1}{8} k_v [\Delta|t|] - Q_e \left( |t\rangle_7 - \frac{1}{8} |t| \right)$$

$$+ g_{s,2}(B) |n_{s,2}|^2$$

$$g_{s,1}(B) = g_{s,2}(B) \left( \frac{1}{2F+1} |t'\rangle - \frac{1}{2F+1} |t\rangle \right)$$

Figure 2. Model of the laser cavity of MGS-COIL used in the simulation.

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where $|i\rangle$ denotes the number concentration of species $i$; $^3\Sigma$ and $^1\Delta$ refer to $O_2 (^3\Sigma)$ and $O_2 (^1\Delta)$, respectively; $I^*$ and $I$ denote atomic iodine in upper level $^3P_{1/2}$ and lower level $^3P_{3/2}$, respectively; $I_F^*$ and $I_F$ denote atomic iodine in the hyperfine level $(^3P_{1/2}, F = F')$ and $(^3P_{3/2}, F = F)$, respectively; $k_f$ and $k_r$ denote the forward and reverse reaction rates of oxygen-iodine energy transfer; $Q_1 = k_4 [O_2]$ and $Q_2 = k_5$ [total] denote the hyperfine relaxation rates of excited level and ground level; $[n_{\Sigma,4}\Sigma^2]$ and $[n_{\Sigma,2}\Sigma^2]$ denote photon number surface density of transition 3–4 and 2–2, respectively. Here we adopt the same assumptions in [15] for atomic iodine: 1) the transition between $I_F^*$ and $I_F$ by the oxygen-iodine energy transfer process is statistical; 2) in each fine energy level, a hyperfine energy level can relax to any other hyperfine energy level with a rate proportional to the statistical weight of the final hyperfine energy level; 3) in each fine energy level, the statistical weight of each hyperfine sublevel is equal. With these assumptions, the rate of pumping a 1 to $I^*$ is proportional to the degeneracy of $I_F^*$ and in each fine energy level, the population of a hyperfine level is proportional to its degeneracy in the absence of energy transfer and stimulated emission.

The rate equations in “slow” group can be express as following:

$$\frac{D}{Dt} \left[ \sum |i\rangle \right] = \frac{D}{Dt} [\Delta] = 0$$

$$\frac{D}{Dt} [I_F^*] = -(k_4 [H_2O] + k_5 [I_2]) [I_F^*]$$

$$\frac{D}{Dt} [I_F] = \frac{2F + 1}{24} (k_4 [H_2O] + k_5 [I_2]) [I^*],$$

where $\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla$ denotes the convective derivative and $\mathbf{v}$ denotes velocity of the gas flow; $k_4$ and $k_5$ denote the quenching rates of $I^*$ by water vapor and by residual $I_2$, respectively.

### 3. Results and discussion

The numerical parameters of laser used in the simulation are mainly refer to the experimental data in [7, 8]. The geometry of laser cavity is shown in Figure 2. A 1.5 m stable resonator consisting of a 99.99% spherical high reflector (HR) and a plane output coupler (OC) is used to extract the energy from the gas flow. The radius of curvature of HR is 10 m and the gain length is set to 25 cm. The computation area of cavity in x–y plane is 7.98 cm × 1.88 cm and the area of aperture is 6 cm × 1.5 cm. Flow conditions in laser cavity are listed in Table 2. The initial small signal gain of line 3–4 is taken to be 0.01/cm.

The executing algorithm used for numerical simulation is presented as follows:

1) Given the flow conditions, magnetic field, total number of steps $n$
2) Initialize flow field in each gain sheet in the absence of optical field by Eq. (8)
3) Compute the optical field and flow field after 8 round trip propagation in cavity by Eqs. (4), (5), (6), and (7)
4) Compute the flow field by Eq. (8)
5) Repeat step 3–4 $n$ times

In our simulation, a $1024 \times 256$ gird is used. The typical time steps is about 0.01 ns (a round trip in cavity), which is small enough in comparison with the laser pulse rise time and all the characteristic time in the kinetic model (see Table 3 in [15]). The calculated output intensity distribution in continuous wave mode is shown in Figure 3. As expected, a scoop-like distribution along flow direction is obtained for the upstream-downstream optical coupling effect in stable cavity.

Before the simulation for different magnetic gain switches, the effect of the reflectivity of OC on laser pulses needs to be determined. Here we adopt an ideal gain switch, which means the gain of medium in cavity is switched from 0% to 100% instantly at $t = 0$ s and keep on this state. The calculated laser pulses with different reflectivity of OC are shown in Figure 4(a). After a sufficient “on” time, the laser turns to operates on continuous wave mode. The peak power and cw power versus reflectivity of OC are shown in

### Table 2. Flow conditions in laser cavity.

| Parameter | Flow rate (mol/s) | T(K) | P (Torr) | Mach |
|-----------|------------------|------|----------|------|
| O$_2$     | 1                |      | 10       | 1.8  |
| I$_2$     | 0.0228           |      | 0.0006   | 0.005|
| H$_2$O    | 0.0005           | 200  |          |      |
| Cl$_2$    | 0.025            | 10   |          |      |
| He        | 3.1              |      |          |      |

Figure 3. Calculated intensity distribution in cw mode. The red rectangle in (a), horizontal red lines in (b) and red vertical lines in (c) represent aperture edges.
Figure 4(b). It is found that the reflectivity corresponding to the max peak power is less than the one corresponding to the max cw power. A lower reflectivity means a higher gain threshold. Thus, the strength of magnetic field required to suppress laser gain below gain threshold is reduced, which helps to reduce the cost and technical difficulties of MGS-COIL. In all following simulations, the reflectivity of OC is fixed at 90%.

For a magnetic gain switch, the most important characteristics are the rise time, residual field, repetition frequency, and duty cycle. Typically, the rise time for a Q-switch of the solid state laser needs to be in nanoseconds. If the Q-switch is not fast enough, the peak power of pulse may be limited by the speed of the switch. However, the small signal gain of COIL is very low so a nanosecond switch is unnecessary for pulsed COIL. In our simulations, the magnetic field is assumed to vary linearly with time. The calculated laser pulses with different rise time are shown in Figure 5(a) and the peak power versus rise time is shown in Figure 5(b). When the rise time is less than 2 μs, the pulse energy of line 2-2 is negligible and the pulse of line 3–4 is not affected by mode competition with line 2-2. When the rise time increases from 2 μs, the pulse energy of line 2–3 increases and the peak power of line 3–4 decreases.

Figure 5. (a) Comparison of laser pulses with different rise time. The dotted line represents the power of line 2-2, dashed line represents power of line 3–4 and solid line represent total power; (b) peak power versus rise time.

Figure 6. (a) Comparison of laser pulses with different residual field; (b) peak power and buildup time versus residual field.
μs to 5 μs, the peak power of line 3–4 suddenly decreases and the peak power of line 2-2 suddenly increases. This is because the pulse of line 2-2 oscillates first and a large amount of $I_0^* = 0$ are consumed, which leads to a significant reduction of $I_0^* = 3$ due to hyperfine relaxation before the pulse peak of line 3–4. As the rise time continues to increase, the peak power of both two lines slowly decreases. Thus, a 2 μs rise time is short enough for a magnetic gain switch to extract the full power of the MGS-COIL.

The residual field is another significant factor that affects the peak power of laser pulses. In practical experiments, it is very hard to cancel the magnetic field perfectly. A nonzero residual field means the gain does not recover to 100% so the peak power of laser pulses will be reduced. The calculated laser pulses with different residual field are shown in Figure 6(a) and the peak power and buildup time versus residual field is shown in Figure 6(b). The rise time is taken to be zero here and the magnetic field is assumed to be uniform. It is shown that the peak power of laser pulses is very sensitive to the residual field which makes it very hard to obtain a hundred percent laser pulse by magnetic gain switch. And the reduction of gain increases the mode buildup time, which makes it necessary to extend the pulse width of pulse magnetic field. For a high frequency magnetic gain switch, an extra 1 μs pulse width of magnetic field will greatly increase the technical difficulties and cost. Thus, it is expected to reduce residual field below 20 G to prevent extra buildup time and energy degrade.

For practical applications, a repetitively pulsed COIL is usually needed. There are two important processes in the operation of a repetitively pulsed COIL: flow refreshing and oxygen-iodine re-pumping, which result in recovery of gain between each two adjacent laser pulse in laser cavity. The calculated laser pulse at 10 kHz is shown in Figure 7(a,b). After one laser pulse, the normalized inversion population recovers fast from 40% to 60% in nearly 2 μs, which is due to oxygen-iodine re-pumping. Then it continues to recover to 100% in about 60 μs by flow refreshing. If the peak power is expected to reach the maximum for all laser pulses, the time interval between two laser pulses needs to be larger than $\frac{A_x}{u}$, where $A_x$ is the length of aperture in laser cavity along flow direction and $u$ is the velocity of the gas flow.

Average power is also an important performance parameter for pulsed COILs. The peak power and average power versus repetition frequency is shown in Figure 8. When the repetition frequency is below 16 kHz
(corresponding to flow refreshing frequency $\nu_{fr}$), the peak power remains to be constant and average power increases linearly, because the gas flow is completely refreshed before every laser pulse. The average power continues to decrease when the repetition frequency exceeds 16 kHz and the peak power continues to decrease when the repetition frequency increases from 16 kHz to 22 kHz but turns to increase a little when the repetition frequency exceeds 22 kHz. That is because the increasing of repetition frequency has opposite effect on the two gain recovery processes: flow refreshing and oxygen-iodine re-pumping (see Figure 7). Since the duty cycle is set to be constant, both the gas flow time between two pulses and the laser pulse duration are reduced by the increasing of repetition frequency. Apparently, the reduction in gas flow time will weaken the gain recovery by flow refreshing process. The reduction in laser pulse duration reduces the consumption of singlet oxygen, which means there is more singlet oxygen remaining to re-pump the atomic iodine. Therefore, the increasing of repetition frequency can enhance the gain recovery by oxygen-iodine re-pumping process. When the repetition frequency begins to exceed 16 kHz, the weaken of gain recovery in flow refreshing process is more significant, so the peak power continues to decrease. When the repetition frequency exceeds 22 kHz, the enhancement of gain recovery in oxygen-iodine re-pumping process becomes more significant so the peak power turns to increase. The frequency corresponding to the minima of the peak power depends on specific gas flow conditions and the optimum repetition frequency is determined by the flow refreshing frequency when the duty cycle is constant.

4. Conclusion

A numerical simulation of the magnetically gain-switched chemical oxygen iodine laser including longitudinal mode competition and hyperfine relaxation is implemented in this paper. The effects of the rise time, residual field and repetition frequency of the magnetic gain switch on the performance of the laser pulse are discussed. The computational results indicate that a rise time below about 2 $\mu$s is good enough to max the peak power of laser pulse and suppress the oscillation of line 2-2. And the optimum repetition frequency is determined by the flow refreshing frequency (10 ~ 20 kHz in common supersonic COILs). Currently, the major challenge for a high performance MGS-COIL is to minimize the residual field to less than 20 G all across the laser cavity. It is expected that the numerical model and computation results presented in this study could provide theoretical guidance for the design of the MGS-COIL device.

Declarations

Author contribution statement

Hao Liu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Kenan Wu: Conceived and designed the experiments; Analyzed and interpreted the data. Lin Wang: Performed the experiments. Yuelong Zhang; Benjie Fang: Contributed reagents, materials, analysis tools or data. Qingwei Li: Analyzed and interpreted the data. Yuqi Jin: Conceived and designed the experiments.

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Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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