RING LASER RESONATOR WITH STIMULATED BRILLOUIN SCATTERING MIRROR

Simona DONŢU¹, Niculae N. PUŞCAŞ², Vasile BABIN³


The results of an theoretical and experimental study of the properties of a ring resonator used with a Nd:YAG laser operating at 1.06 μm are presented. The rates equations are presented in a rotative system for an optical field distribution and inversion population obtaining the oscillation conditions of a ring laser resonator. With this model a kinetic model for a ring laser resonator with stimulated Brillouin scattering mirror (SBS) was developed. The ring laser resonator contains four plane mirrors and a Nd:YAG rod with a small signal single pass gain. A Brillouin mirror contains a cell with CS₂ is put behind of a lens in exterior of ring resonator. The laser works in free regime with a low coefficient laser resonator. When the intensity of laser radiation increases in the resonator, barrier of the stimulated Brillouin diffusion grows out of and the reflectivity of cell increase, so that the coefficient of resonator is switched.

Using a fast photodiode and a digital oscilloscope (2GHz) we measured the duration of the laser pulse and the energy with a Mollectron detector. The transversal structure of output radiation intensity was monitorised using a CCD camera and a SPIRICON system.

Keywords: stimulated Brillouin scattering, ring laser resonator, SBS mirror

¹ Researcher, National Institute for Optoelectronics, INOE 2000, Romania
² Prof., Physics Department I, University POLITEHNICA of Bucharest, Romania
³ Researcher, National Institute for Optoelectronics, INOE 2000, Romania
1. Introduction

Phase conjugation via stimulated Brillouin scattering (SBS) has been demonstrated to be a simple and very efficient method for dynamically correcting the aberrations in solid state lasers [1-5]. First Q-switching of the laser resonator using SBS was applied for ruby lasers and then for Nd:YAG lasers [4].

The approach usually adopted is to include the SBS medium inside a laser cavity with a secondary mirror employed to provide feedback at the beginning of the laser action [7,8]. High intra-cavity intensities experienced by the SBS medium in this configuration can lead to poor spatial beam quality. This limits the repetition rate and peak power of the output.

SBS was extended for Q-switching down to the UV wavelength range, for excimer laser [9] till the IR domain, for Er lasers [10, 11].

In this article, we investigate experimentally and theoretically the performances of a pulsed Nd:YAG laser system utilising external stimulated Brillouin scattering for Q-switching and phase conjugation of the cavity radiation for ring laser resonator. In comparison with the linear configurations, where each round trip the laser beam travels within the cavity will generate a downshifted Stokes beam and therefore will increase the bandwidth of the laser emission, the ring configuration allows the potential of single frequency operation from the resonator. In the ring configuration, the Q-switching regime is obtained in a novel oscillator two-pass amplifier system [11,12]. The ring resonator geometry was used also for a dye laser with SBS Q-switching mirror.

2. Theoretical model of SBS ring laser

The system describing the Q-switching regime is the same as in the case of the linear resonator [13].

\[
\frac{dq}{dt} = q[Bn - \gamma_{nl}(q)]
\]

\[
\frac{dn}{dt} = -qBn
\]

where: \(q\) is photon density, \(n\) is the population inversion, \(n_{th}\) is the inversion at generation threshold, \(B\) is Einstein's coefficient and \(\gamma_{nl}(q)\) are the losses which depend on intensity due to the dependency of the SBS reflection coefficient, \(R\), on intensity. The initial population inversion, \(n(0)\), is assumed above the threshold as the term \(1+\zeta(\zeta\sim2\%)\).
The threshold condition for the two intensities $I_a$ and $I_c$ are derived considering an imaginary plane between the polarizer and mirror $R_l$:

$$I_a R_l TR_1 R_4 e^{(\gamma c - \gamma a) l_0} R_4 (1 - R_{out}) + I_c R R_{out} = I_a$$

$$I_c (1 - R_{out}) R_4 e^{(\gamma c - \gamma a) l_0} R_4 R_1 T R_1 = I_c$$

where $R_{out}$ is the reflectivity of the output mirror (polariser), $R_1=R_2=R_3=R_4=100\%$, $T$ is the transmission of the saturable absorber ($T=30\%$), and $l_r$ is the rod length and $\alpha$ are the losses per unit length of the laser rod.

We define:

$$\delta = \frac{I_c}{I_a}$$

Thus, the nonlinear losses $\gamma_{nl}(q)$ have the form:

$$\gamma_{nl} = \gamma_c + \gamma_a = 2\alpha \frac{1}{l_c} \ln \left( \frac{1 - R R_{out}}{[1 - R_{out}] T R_1 R_4 R_2} \right)$$

where $\tau = l_0/c$ is the round trip time of the resonator. In the expression of the nonlinear losses we neglect the term referring to the linear losses $2\alpha l_0 l_r$, which is very small.

The steady state theory of SBS have been considered again to find the analytical solution for $R$:

$$\frac{\exp(-G)}{R} = \frac{1 - R}{\exp[(1 - R) g_B L_{eff} I] - R}$$

where $G\sim25$ is referring to the initial Stokes noise, $g_B$ is the Brillouin gain and $L_{eff}$ is the interaction length which depends on the focal length of the focalizing lens.

Photon density in the laser resonator is:

$$q = \frac{2}{c h \nu} (I_c + I_s)$$

where $I_s$ is Stokes density.

Introduceing the normalised variables:

$$\zeta = \frac{l_0}{l_r}$$

$$R(\zeta) = \frac{I_s}{I}$$

$$y(\zeta) = \frac{n(\zeta)}{n(0)}$$

$$x(\zeta) = (1 + I_s) g_B L_{eff}$$

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$$\exp(-G) = \frac{1 - R}{\exp[(1 - R) g_B L_{eff} I] - R}$$

$$q = \frac{2}{c h \nu} (I_c + I_s)$$
we obtain the following equation system:

\[
\frac{dR(\zeta)}{d\zeta} = [A_0 y - G(R)]C(R) \\
\frac{dy(\zeta)}{d\zeta} = -B_0 y x \\
\frac{dx(\zeta)}{d\zeta} = [A_0 y - G(R)]x
\]  \hspace{1cm} (8)

The third equation in the system (8) represents the dynamics output pulse equation. The initial conditions are:

\[ R(0) \approx e^{-G} y(0) = 1; x(0) \approx e^{-G} \]  \hspace{1cm} (9)

and respectively:

\[
\begin{align*}
A_0 &= \tau B n(0) \\
B_0 &= \frac{2 \tau B}{c h v g_{B} L_{eff}} \\
G(R) &= \ln \left[ \frac{1 - R R_{out}}{[(1 - R_{out}) T R_1 R_2 R_3 R_4]^2} \right] \\
C(R) &= \frac{2 R + \frac{1}{1 - R^2} \frac{1 + (1 - R)e^G}{1 + (1 - 2 R)e^G} \ln[R + R(1 - R)e^G]}{R(1 - R^2)}
\end{align*}
\]  \hspace{1cm} (10)

The results of the numerical simulations are presented in Fig. 1.

Fig 1. Brillouin reflexion coefficient R (curve 1), population inversion (curve 2), output pulse (curve 3) versus time, for \( R_{out} = 0.5 \)
3. Experimental set-up

The experimental set-up is depicted schematically in Fig. 2 [1]:

![Fig. 2 The experimental SBS ring laser resonator](image)

The four plane mirrors with reflectivity R~100% and the Nd:YAG rod with a small signal pass gain of ~100 defined the ring cavity, whose length was 1 m. The Nd:YAG rod with a 6 mm diameter and a 90 mm length was pumped by a flash lamp in a diffuse, liquid cooled cavity. The radiation at 1.06 μm was outcoupled by a half-wave plate-polariser combination. The Brillouin Cell (L = 10 cm) filled with CS₂ was placed behind a lens, which had a focal length of 10 cm, outside the ring cavity. The Brillouin backscattering radiation returned to the ring resonator has been extracted through the polarizer cube to be analysed.

A fast photodiode and a Le Croy digital oscilloscope (2GHz) have been used to monitor laser pulse durations. Mollectron detectors have been used to measure laser beam energies. The transversal structure of the output radiation was monitored by a CCD camera and a SPIRICON system.

4. Experimental Results

We used a saturable absorber (Kodak liquide saturable absorber for Nd:YAG laser radiation) to initiate the SBS process. It was mounted in the cavity and aligned such the reflection of the windows cell would not cause feedback and the transmission was reduced until a single Q-switched spike was obtained. This has the additional effect of pre-Q switching the laser yielding pulses of duration ~50 ns in the clockwise (Ic) and anti-clockwise (Ia) directions.

The output, Io, was incident on the cell containing CS₂. Reflection from the SBS cell reinjected, Ic, back into the ring where it contributed to the flux, Ic. The
clockwise travelling output from the rod, via polariser, was p-polariser and after one pass through the half wave plate became s polarised component and was focused into the SBS cell. Because the SBS interaction preserves the polarisation corresponded to the first Brillouin Stokes shift \( \omega_1 = \omega_0 - \omega_B \), where \( \omega_0 \) is the linecentre of the Nd:YAG crystal and \( \omega_B \) is the acoustic frequency. After one complete round trip \( s_0(\omega_1) \) was converted to \( p_1(\omega_1) \) by the half wave plate and then made a second round trip before reconversion back into \( s_2(\omega_1) \) and emission through polariser as the output. The cavity therefore acts as an oscillator-two pass amplifier system.

The laser presented in Fig. 2 started in the free-running regime with a low Q factor determined by the losses of the cell and the saturable absorber. The SBS reflectivity of the cell increased rapidly with the incident wave intensity and the ring resonator with the Brillouin mirror reached a high Q factor.

The output beam with an energy of 40 mJ in a pulse of 15-20 nsec duration was obtained at 2Hz. At higher repetition rates Q-switching action becomes unreliable due to the fact that the saturable absorber was not circulated and excessive thermal loading may appear.

A typical output pulse with a width (FWHM) of 15 nsec is show in fig. 3:

![Fig. 3 A typical output pulse of SBS ring laser](image)

The experimental results (fig. 3) are in a good agreement with the theoretical results (curve 3 from fig. 1).

The Q-switched laser was partially mode-locked indicating that there exist many longitudinal modes oscillating during the lasing process.

Under proper alignment of laser mirrors, and with an aperture of \( d = 1.5 \) mm the laser could operate in the TEM\(_{00}\) mode and the energy of the pulses diminished to 5 mJ.
5. Conclusions

We demonstrated a SBS Q-switching of a ring resonator based on the gain material Nd:YAG. The power generated in the free-running regime proved to be not enough to reach the threshold of the SBS process in the cell. However we succeed to start operation of the laser in the Q-switching regime using a saturable absorber.

A theoretical description of the external SBS Q-switching resonators has been developed, using the stationary approximation for the SBS interaction and good agreement between experimental data and theory was obtained, even our model is very simple in comparison with Lamb’s model which uses the general equation model but does not take into account the propagation effects within the resonator and the subsequent frequency shift which is characteristic for SBS.

REFERENCES