Tunable Cavity Parameters

Polarization-based Laser Resonator Cavity

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The setup assembled for the purpose of carrying out experiments on Polarization based Laser Resonator Cavity

ABSTRACT

We have developed a polarization-based laser resonator cavity which provides continuous tuning of various cavity parameters preserving the cavity alignment. The cavity houses intracavity polarization optics inside a confocal resonator. The resonator cavity facilitates continuous tuning of the output coupling and allows flexible optimization of various laser parameters like output energy, cavity buildup time, and laser pulse width at different pump pulse energies. The optimum output coupler reflectivity of a laser system can be accurately determined at different input pump power levels using this resonator configuration. The resonator cavity also allows accurate determination of the round trip resonator losses and small-signal gain coefficient of a laser system. This system can be useful for all-optical synchronization of multiple laser pulses as desired in many spectroscopic experiments.

KEYWORDS: Polarization-based resonator cavity, Variable output coupling, Gain coefficient, Round trip resonator losses, Gain-coefficient, Delay synchronization

Introduction

The extraction efficiency of a laser resonator cavity with fixed resonator losses depends on the total gain of the system and the reflectivity of the output coupler. The gain of the system is a function of the input pump power. Hence, it is a tedious task to optimize the output power of a given laser resonator cavity as the input pump power is changed. The optimum coupling from a particular gain medium is generally achieved by replacing several output couplers of different reflectivity [1-2]. Apart from being tedious, this methodology has limitation in respect to reproducibility and reliability. This is because each time after replacement of the output coupler, the resonator cavity has to be realigned. Various other techniques like a dielectric-coated tapered reflector, Gaussian reflectivity mirror, Michelson interferometer-based reflector, Fabry-Perot interferometer based reflector, Frustrated Total Internal Reflection (FTIR) based reflector, and anti-resonance ring interferometer have been tried for continuously varying the reflectivity of the output coupler with their trade-off [3-7].

We have designed and developed a polarization-based laser resonator that allows continuous tuning of the output coupler reflectivity without any misalignment to the cavity. The laser resonator cavity was developed and studied using Cr:forsterite as the gain medium. Various cavity parameters like output energy, intracavity energy, buildup time, laser pulse width, and threshold pump pulse energy are studied as a function of the output coupling at different pump pulse energies.

Experimental Setup

The schematic of the experimental setup of the polarization-based laser resonator cavity is shown in Fig. 1. A Cr:forsterite crystal having a dimension of 5 mm x 5 mm x 12 mm is used as gain medium in this experiment. The crystal has an absorption coefficient of 1.47 cm^{-1} at 1064 nm for polarization along *b*-axis (E II b) and a Figure Of Merit (FOM) of 17. The crystal is pumped by the fundamental frequency (1064 nm) of a Q-switched Nd:YAG laser having a pulse repetition rate of 10 Hz. The pump beam has a diameter of 8 mm and a divergence of 0.5 mrad. The pump beam is focused slightly away from the crystal to avoid damage, using a 1000 mm focal length lens (L). The intensity of the pump beam is varied using a half-wave plate and a polarizing beam splitter (PBS).

The laser resonator cavity consists of two high reflecting concave mirrors (M1 and M2) in confocal geometry, an intracavity polarizing beam splitter cube (I-PBS), and a retardation plate (RP). The high reflecting concave mirrors have a radius of curvature of 100 mm, the reflectivity of >99% at 1150 -1350 nm, and the transmission of ~ 98% at 1064 nm. The pump polarization is made collinear with *a*-axis of the crystal by using a half-wave plate ($\lambda/2$ plate) placed before the crystal and the beam emerging from the crystal is vertically polarized. The reflectivity of the output coupler is varied using the Retardation Plate (RP), placed in between the I-PBS and

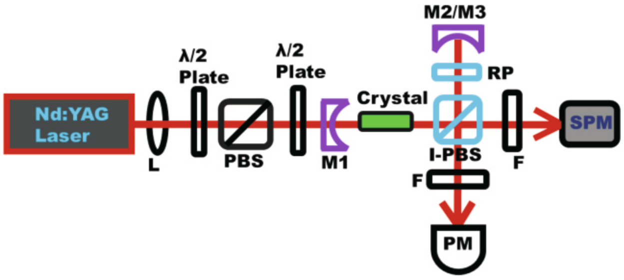

Fig.1: Schematic of the experimental setup of the polarization-based Cr:forsterite laser resonator cavity. L: 1000 mm focal length lens; PBS: polarizing beam splitter, M1, M2: concave mirrors, roc:100mm, R: 99% @1150-1350nm, T: 98% @1064nm; M3: concave partial reflecting mirror, roc:100 mm, R:95%@1150-1350 nm; I-PBS: intracavity polarizing beam splitter; RP: retardation plate; PM: power meter; F:1064 nm filter; SPM: spectrometer.

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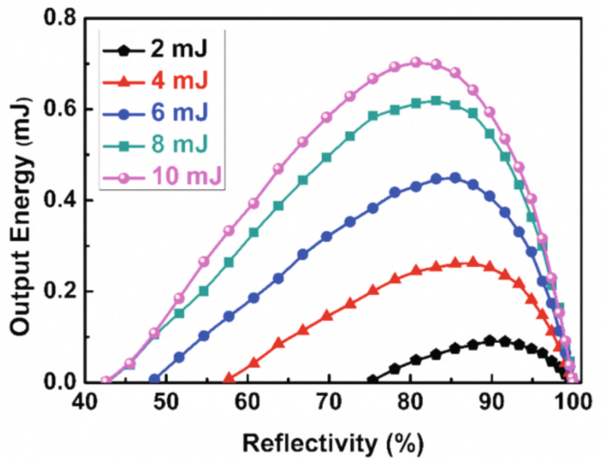

Fig.2: Variation of the output energy of the resonator cavity as a function of the output coupler reflectivity for different pump pulse energies.

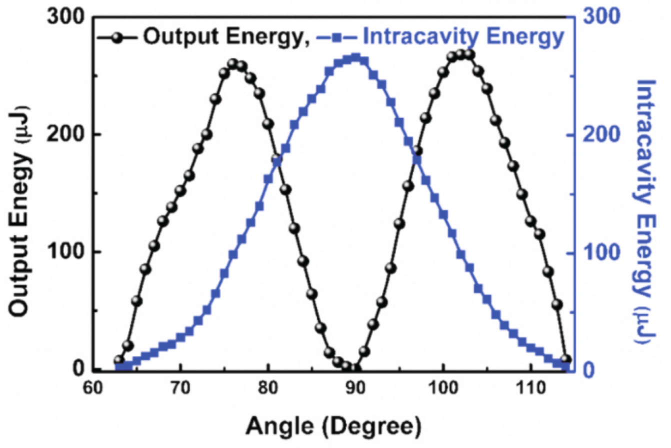

Fig.3: Variation of the intracavity energy and cavity output energy as a function of retardation plate angle.

mirror M2. The intracavity beam reflected from the I-PBS oscillates in between the resonator mirror M1 & M2 and the laser output is obtained through the transmission part of the I-PBS along the orthogonal direction. The state of polarization of the laser beam as well as the laser output energy can be controlled by changing the angle of the retardation plate.

The output coupler reflectivity is calculated from the angle of rotation of the retardation plate using the Jones matrix formalism and found to be varied from 100% to 13% at Cr:forsterite laser wavelength[8].

Results & Discussion

Study of Cavity Output Energy

The variation of the output energy of the resonator cavity with the reflectivity of the output coupler at different pump pulse energies is shown in Fig.2.

For a particular pump pulse energy, the output energy increases with an increase in the output coupler reflectivity becomes maximum and then decreases. The intracavity energy increases with an increase in the output coupler reflectivity which increases the output energy. The transmission of the output coupler decreases with an increase in the output coupler reflectivity which results in a decrease in the output energy. Hence, the output energy has an optimum value at certain reflectivity of the output coupler (for a fixed pump pulse energy and resonator losses). For a laser system, the value of optimum output coupler reflectivity will be different at different pump pulse energies. The polarization-based laser resonator provides optimization of the laser output energy at different pump pulse energies by simply rotating the retardation plate. This doesn't require a change in any other components of the laser system. From Fig.2 it can also be observed that the lasing output starts at a certain value of output coupler reflectivity known as the threshold output coupler reflectivity. Fig.2 shows that both the optimum and threshold output coupler reflectivity value is shifting towards the lower value with the increase in the pump pulse energy. The gain of the system increases with the pump pulse energy, hence even lower feedback from the output coupler can overcome the resonator losses. Therefore, the resonator threshold and the optimum output energy are achieved at a lower value of output coupler reflectivity. For lower pump energy, the gain is small, hence higher feedback is required to overcome the resonator losses. Therefore, the resonator threshold, as well as the optimum output coupling occurs at higher a value of reflectivity. The polarization-based laser resonator cavity provides an accurate determination of the threshold and optimum output coupler reflectivity value of a laser system at different pump pulse energies.

Study of Intracavity Energy

The variation of intracavity energy of the resonator with the output coupler reflectivity is studied by replacing the high reflecting concave mirror M2 with a 95% reflecting concave mirror M3 and shown in Fig.3. The transmitted energy through M3 is proportional to the intracavity energy.

The intracavity energy is zero when the total gain of the system can not overcome the total resonator losses. This defines the lasing threshold and the corresponding reflectivity of the output coupler is the threshold output coupler reflectivity. The intracavity energy is maximum for retardation plate angle at 90^{0}, which corresponds to output coupler reflectivity of 100%. Thus, the output energy of the resonator cavity is zero. As the retardation plate is further rotated beyond 90^{0}, the intracavity energy decreases from its maximum value with a decrease in the output coupler reflectivity and becomes zero at the threshold reflectivity value.

Study of Buildup Time and Laser Pulse Width

The buildup time of a laser plays an important role in the temporal delay synchronization of multiple laser beams. For several laser spectroscopic experiments like resonance ionization spectroscopy, multiphoton absorption spectroscopy, coherent ant-stoke Raman spectroscopy (CARS), the delay of multiple laser beams needs to be synchronized. This is normally achieved either by electronic delay or by external optical delay. For this purpose, the polarization-basedresonator cavity can be a good choice where the cavity buildup time, and hence the delay of the laser beam can be optically varied continuously. The variation of the cavity buildup time and laser pulse width (FWHM) is studied as a function of the output coupler for different pump pulse energies as shown in Fig.4.

The cavity buildup time decreases with an increase in the reflectivity of the output coupler for a fixed pump pulse energy. The cavity buildup time also decreases with an increase in the input pump energy as higher gain leads to faster growth of the signal with a fixed cavity loss. The cavity buildup time can be continuously tuned from a few tens of ns to a few hundred ns

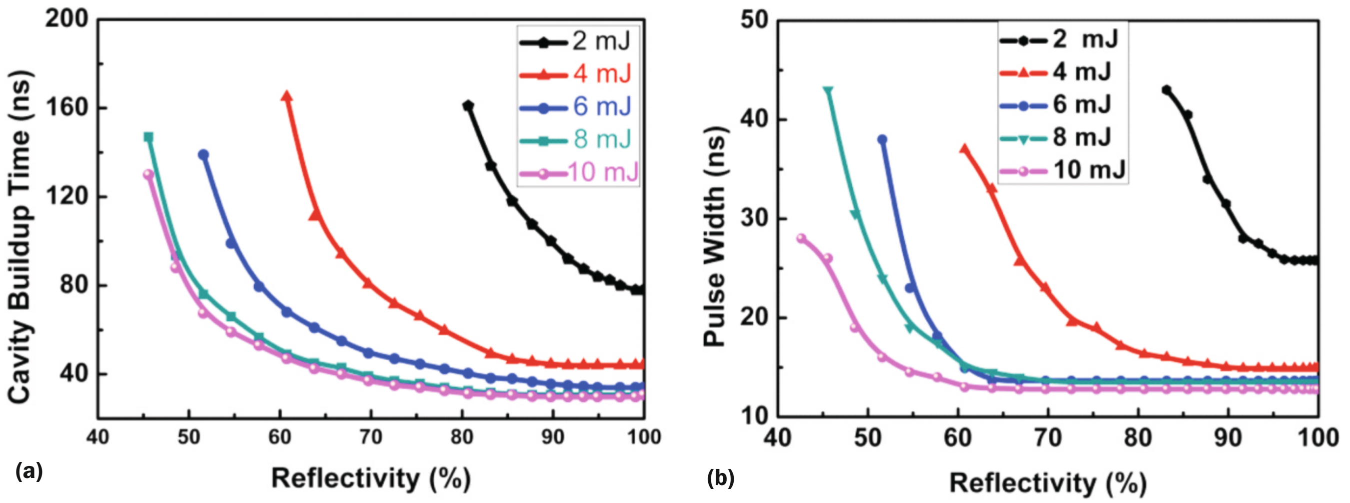

Fig.4: (a, b). Variation of cavity buildup time and laser pulse width with output coupler reflectivity for different input pump pulse energies.

and hence can be used to precisely control the delay of the laser beam. The laser pulse width decreases with an increase in the reflectivity of the output coupler and finally reaches a plateau. From Fig. 4(b), it can be observed that the laser pulse width remains constant over a wider range of reflectivity (~65-99%) at higher pump pulse energy (> 4mJ). In this range, the buildup time can be varied by simply rotating the retardation plate while maintaining the pulse width constant. Hence, the resonator cavity provides precise delay control of laser pulse which can be used in many spectroscopic applications delay synchronization.

Study of Threshold Pump Pulse Energy

The polarization-based laser cavity provides an accurate method of measuring the threshold pump energy for different values of the output coupler reflectivity without disturbing the cavity alignment, unlike the conventional method of changing the output coupler. This allows the determination of round trip resonator losses and gain-coefficient of laser system using the Findlay-Clay analysis in which the threshold pump energy is measured as a function of output couplers reflectivity [9].

Fig. 5 shows the variation of the input threshold pump energy (E_{th}) versus output coupler reflectivity (-lnR), from which the roundtrip resonator losses (δ) and the small-signal gain coefficient (g_0) of the system are determined using the laser threshold condition.

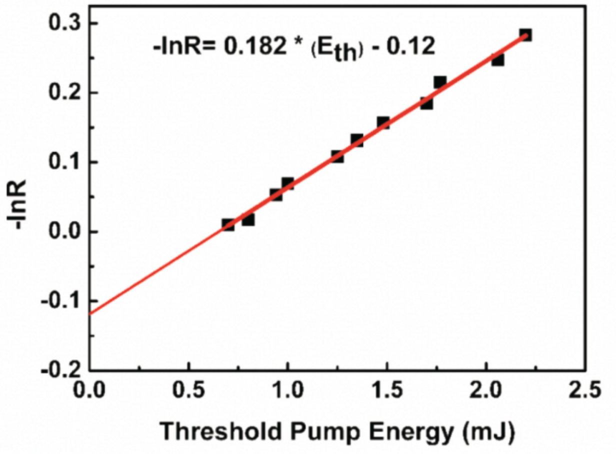

Fig.5: Threshold pump energy (E_{th}) as a function of the output coupler reflectivity (-lnR).

$$2g_0 l = \delta - lnR \approx \delta + T, \text{ and } -lnR = \frac{2\eta}{AI_s} E_{th} - \delta$$

where l, A, I_s and η are the length of the crystal, the effective cross-sectional area of the crystal, the energy density inside the laser resonator, and the total efficiency of the laser respectively [10]. Consequently, the δ and g_0 are found to be 12% and, 0.076 x E_{in} (cm^{-1}) respectively [11]. The small-signal gain coefficient (g_0) of the system at the threshold pump energy of 0.65 mJ is 0.045 cm^{-1}.

Conclusions

A polarization-based resonator cavity is developed using an intracavity polarization beam splitter cube, and a retardation plate inside a confocal resonator using Cr:forsterite crystal as the gain medium. The rotation of the retardation plate facilitates continuous tuning in the output coupling without disturbing the cavity alignment. The cavity output energy, cavity buildup time, laser pulse width, and the threshold pump energy are measured as a function of the output coupler reflectivity. The round trip resonator losses and small-signal gain coefficient of the system are determined using Findlay-Clay analysis at the laser threshold. The developed resonator cavity provides *in situ* control of the laser pulse delay without changing the laser pulse width which can be used in many spectroscopic experiments for delay synchronization. It also provides an ideal platform for the study of the basic mechanism associated with laser physics.

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