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Amplitude Noise Reduction of Ion Lasers With Optical Feedback

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Abstract

A reduction in amplitude noise on the output of a multi-mode continuous-wave Ar-ion laser was previously demonstrated when a fraction of the output power was retroreflected back into the laser cavity. This result was reproduced in the present work and a Fabry-Perot etalon was used to monitor the longitudinal mode structure of the laser. A decrease in the number of operating longitudinal cavity modes was observed simultaneously with the introduction of the optical feedback and the onset of the amplitude noise reduction. The noise reduction is a result of a reduced number of lasing modes, resulting in less mode beating and amplitude fluctuations of the laser output power.

Introduction

Seeding a laser cavity with external radiation has long been known to improve some characteristics of broadband laser outputs [1]. Several studies have shown that retroreflection of a small fraction of the laser output back into the laser cavity as optical feedback can reduce the amplitude noise of the output on fast time scales (nanoseconds to milliseconds). Noise reduction by retroreflection has been experimentally demonstrated [2-4] and numerically modeled [5-7] for synchronously-pumped mode-locked lasers. Subsequent to this initial work, similar noise reduction was also observed [8] for a multi-mode continuous-wave (cw) Ar-ion laser. In this note the noise reduction effect of Ref. 8 was reproduced while monitoring the longitudinal mode structure of the laser with and without feedback. This allows changes in the laser frequency content associated with the introduction of optical feedback (and the onset of noise reduction) to be observed.

The experimental portion of the present work was performed in the mid-1990s during preparations [9-13] for the use of stimulated Raman scattering as a nonintrusive supersonic wind tunnel diagnostic [14] at Langley Research Center (LaRC). But the work was not documented at that time because of various time constraints. More recently other researchers published comprehensive work [15, 16] performing essentially the same study as described here. It was decided to document the unpublished LaRC cursory study to demonstrate consistency between the results of two different studies: the present LaRC work and that of Ref. 8.

Experiments and Results

The experimental setup for the present work is shown in the schematic of Fig.1. A retroreflecting mirror was positioned one cavity length (170 cm) from the output coupler of a large-frame cw Ar-ion laser that was operated in a single line (514 nm) multi-longitudinal-mode configuration, i.e., without an intra-cavity etalon. Either a phase conjugate mirror (PCM) or conventional mirror (CM) can be used to accomplish the retroreflection and the associated noise reduction. The PCM used in this work was a pooled $BaTiO_3$ crystal. A variable transmission filter (VTF) was used to vary the fraction of output light that is seeded back into the laser cavity in order to optimize the noise reduction. As shown in the figure, the laser output beam was divided with beam splitters (B/S), and portions were monitored with low and high speed photodiodes (PD) and a scanning Fabry-Perot (FP) etalon with free spectral range = 2 GHz and finesse = 150. Both PDs and the etalon are monitored with oscilloscopes. The polarization rotator is necessary only when using the PCM; it can be removed when using a CM.

A clear reduction of amplitude noise in the time domain signal from the high-speed photodiode is observed when the back reflected beam (i.e. feedback) is admitted into the laser cavity by removing a beam block located just in front of the retro-mirror. Simultaneous with the noise reduction, the number of longitudinal modes that are observed (on the scanning FP etalon) to be lasing is significantly reduced. Both of these results are obtained whether using the PCM or CM as the retroreflector. Translating the retro-mirror away from the one-cavity position, by 10 cm or more, eliminates the noise reduction for the 170-cm cavity length laser.

An example of the spectral result is shown in Fig. 2 using the PCM as the retroreflector. In this case about 50 % of the incident beam was reflected back towards the laser cavity as a phase conjugate beam. Fig. 2a shows ≈ 1.8 free spectral ranges of the FP etalon output displayed on an oscilloscope trace, as the FP etalon is scanned over the laser spectrum. For Fig. 2a, the beam is blocked just in front of the PCM (i.e. no optical feedback into the laser cavity). The horizontal white doubled-headed arrow indicates the width of one etalon scan or one complete laser spectrum. In both Figs. 2a and 2b the scan is repeated almost for two full etalon free spectral ranges. Thick vertical green arrows show the locations of the etalon retraces, where the etalon scan stops and starts over again. Fig. 2b shows the laser spectrum with the block removed and the VTF adjusted for about 8 % transmission in one pass.

The fraction of laser output that is seeded back into the Ar-ion laser cavity as feedback in this case is estimated to be about 10^{-4} after accounting for the large reflectivity of the laser output mirror. The oscilloscope time scale (equivalent to frequency domain for the scanning FP etalon) is the same in Figs. 2a and 2b, where the scan is over a frequency range equivalent to about two free spectral ranges of the etalon. However, the vertical sensitivity is changed by a factor of five for Fig. 2b relative to 2a. Green vertical arrows indicate the end of each etalon scan and the voltage retrace back to the beginning of the next scan. The hash seen in Fig. 2a is the result of a vast number of low intensity longitudinal modes that are lasing during the ≈ 4 ms that it took to scan the etalon over one free spectral range. In contrast Fig. 2b shows only a few modes lasing during a similar 4-ms scans. Each sharp vertical spike in Fig. 2b represents one longitudinal laser mode, except for the last spike on the extreme right-hand side which is an artifact of that etalon retrace. Since each observed mode in Fig. 2b could be lasing at a different brief time during the 4-ms scan, the few observed modes are not necessarily lasing simultaneously.

An example of the time domain result is shown in Fig. 3. In this case, the noise reduction and spectral narrowing were accomplished by replacing the PCM with a conventional plane mirror. Fig. 3a shows a typical short temporal window of the laser output power fluctuations from ac-coupled high-speed PD (rise time ≤ 0.5 ns) without any feedback into the laser cavity (i.e. retroreflected beam blocked beam). The sinusoidal-like wave pattern is an ≈ 85 MHz oscillation in the laser output power that is generated from the mode beating of adjacent longitudinal cavity modes. Harmonics of 85 MHz, due to beating of modes that are not nearest neighbors, are weaker and not apparent. In Fig. 3b, with the addition of feedback (i.e., beam block removed), the fluctuation at 85 MHz is reduced beyond the detection level of the PD with the same vertical sensitivity as in Fig. 3a. Lack of a strong 85 MHz oscillation shows that adjacent longitudinal modes are not effectively lasing simultaneously. The laser is probably switching from one mode to another sequentially, as illustrated by observation of more than one mode in the time-averaged (4 ms) etalon scan of Fig. 2b.

The experiment described above with an Ar-ion laser was repeated with a 15-mW 633-nm He-Ne laser (70-cm mirror separation) and with a 0.2-mW 544-nm He-Ne laser (25-cm mirror separation). For both He-Ne Lasers, a reduction of the number of lasing modes was again observed simultaneously with an amplitude noise reduction when a fraction of the output was retroreflected back into the cavity. In each case, the retroreflecting mirror was usually located one cavity length from the laser output mirror. Finally, noise reduction was also measurable with both types of retroreflecting mirrors, on both the Ar-ion and the smaller He-Ne Lasers, if the retroreflecting mirror was placed at a location corresponding to one half of the mirror separation for the laser.

Summary

The results presented here show that the noise reduction in cw ion-lasers from retroreflection schemes such as reported in Ref. 8 occurs due to a reduction in the number of longitudinal modes that are lasing. Retroreflection of a portion of the laser output back into the laser cavity is equivalent to seeding the laser cavity with all operating modes, but the few largest modes dominates over the other slightly weaker modes in the mode competition during the non-linear amplification process inside the laser cavity – possibly to the extent that only a single mode is lasing at any one brief time. This results in less mode beating and amplitude noise to the point of complete elimination of mode beating noise if only one mode remains lasing. The results of the present work are in agreement with previous studies [15, 16] that tested this same hypothesis with similar and more extensive measurements. Similar results of noise reduction have also been obtained by retroreflection with cw [17] and mode-locked [18] diode lasers.

If a modest loss in laser power can be tolerated (e.g., a factor of 2 or less) similar or better noise reductions can be achieved in ion lasers by inserting an etalon inside the laser cavity and forcing the laser to operate smoothly on a single longitudinal mode. In this way the noise reduction can be achieved without the external optics necessary for the phase conjugate reflection process. However if very little laser power can be sacrificed for noise reduction, Ref. 8 demonstrates that only a few percent of the beam was necessary to achieve significant noise reductions using a phase conjugate mirror.

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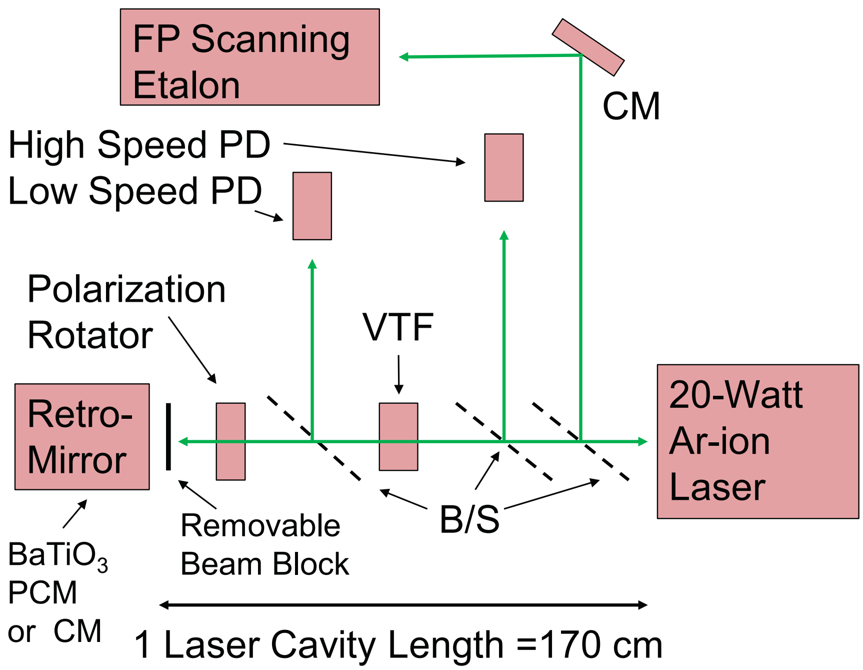

Fig. 1. Schematic of the setup used for observing amplitude and frequency characteristics of the laser output when providing optical feedback into an Ar-ion laser cavity.

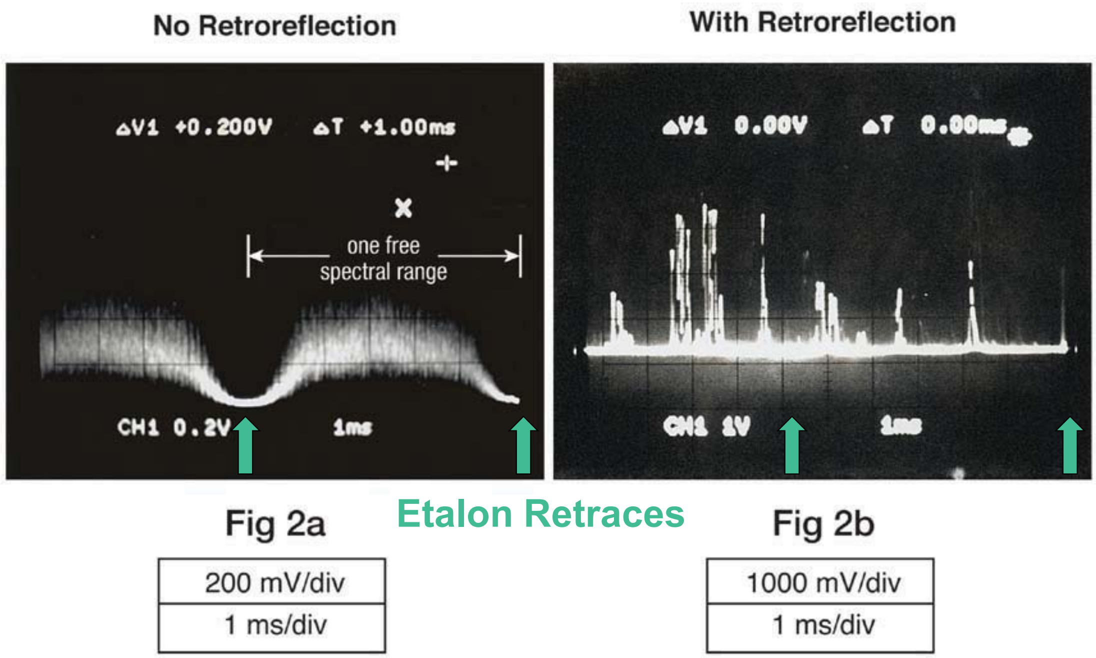

Fig. 2. Frequency spectrum of Ar-ion laser (a) without feedback showing so many lasing modes that the spectrum appears as hash and (b) with optical feedback from a $BaTiO_3$ PCM showing a greatly reduced number of modes.

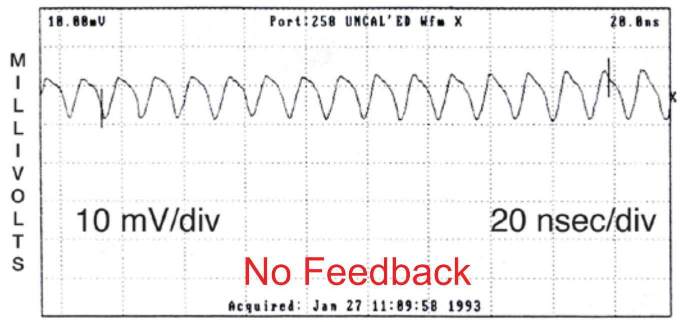

Fig 3a

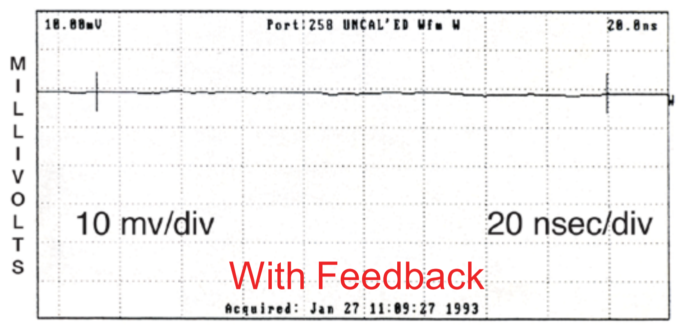

Fig 3b

Fig. 3. Time trace of Ar-ion laser output (a) without feedback showing 85 MHz oscillations due to mode beating between adjacent longitudinal modes and (b) with feedback from a conventional mirror showing significantly reduced oscillations.

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14. ABSTRACT

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