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INJECTION LOCKING OF EXCIMER LASERS

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Abstract

Reliable injection locking of high-power unstable resonator excimer lasers can be achieved with extremely low reference oscillator power. The criteria for injection locking are discussed and experimental results are given.

Introduction

The channeling of the energy of high-power excimer lasers into very narrow spectral bandwidths in low divergence beams is a prerequisite for many potential applications of these lasers. High spectral brightness is required for spectroscopic applications and optical harmonic generation [1,2] and the long coherence length associated with a narrow bandwidth is required for nonlinear phase conjugation, backward stimulated Brillouin and Raman scattering [3] among other applications.

It is by now well recognized that the simplest way to control the spectral bandwidth and beam divergence of high-gain excimer lasers is by the combined implementation of an unstable resonator and injection locking. This conclusion is not new nor is it without precedent. Injection locking has long been recognized as a way to lock the frequency of a high-gain broadband oscillator to the frequency of a low-power narrow-bandwidth reference oscillator.[4] This technique has been applied successfully to unstable resonators for CO_2 lasers[5] as well as for dye lasers.[6] It has also been used previously to narrow the bandwidth and reduce the divergence of high-gain unstable-resonator excimer lasers.[7,8]

The technique is attactive because near-diffraction-limited output and ultranarrow linewidth can be achieved with no loss of laser efficiency. Moreover the attractiveness of the technique is enhanced by the fact that very little reference oscillator power is required to achieve those parameters. The contribution of our work has been to determine (and obtain) the theoretical minimum required injected power for reliable locking,[9] and to achieve transform-limited bandwidth in an injection-locked excimer system[10] (also with ultralow reference oscillator power).

We review in this paper the criteria which determine reliable injection locking of unstable resonator excimer lasers (or other high-gain lasers) with minimal injected power. Experimental confirmations are also reviewed.

The Parameters of Concern

To achieve reliable locking of a power oscillator (PO) it is necessary that the field intensity from the reference oscillator (RO) exceed the spontaneous emission noise in all transverse modes which can resonante in the PO. Thus the use of an unstable resonator for a PO of large mode volume will greatly reduce the required injected RO power. This is due to the fact that much fewer transverse modes can oscillate in a properly chosen unstable resonator when compared with a stable resonator of equal mode volume. In the case of a confocal unstable resonator with properly chosen magnification, it is posible to injection lock with an RO power which exceeds only the noise in a single transverse mode. For KrF lasers this means that a 10 MW device can be reliably injection locked with less than 1 W of injected power.[9] The divergence of the output beam in Ref. 9 was near (< 1.5 times) the diffraction limit.

The experimental arrangement for achieving these results is shown in Fig. 1. The RO beam is injected through a small hole in the rear optic of the unstable resonator. An efficient mapping of the injected beam onto the lowest-order mode (LOM) of the unstable resonator is easily effected if the injected beam has its beam waist (i.e., is collimated) at the surface of the unstable resonator output coupler. This mode mapping efficiency is optimized if that beam waist diameter is 1/M times the output coupler diameter. The arrangement shown in Fig. 1 also facilitates alignment of the unstable resonator.

Even if the injected beam has been efficiently mapped onto the LOM, the minimum injected power required for locking will still not be achieved if the unstable resonator "prefers" to oscillator on, say, mode #2 rather than the LOM. Siegman and Miller[10] have

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shown that the cavity losses for the first few modes, of an unstable resonator, oscillate as a function of the equivalent Fresnel number, N_{eq}, which is defined as follows

$$N_{eq} = \frac{a^2}{\lambda L} \left[\frac{g_1}{g_2} (g_1 g_2 - 1)\right]^{\frac{1}{2}}$$

where a is the laser tube radius, L is the cavity length and $g_i \equiv 1 - L/R_i$ is the usual stability parameter. Therefore, it is important to select the N_{eq} of the cavity (by adjusting L or λ) such that the LOM is the mode which will experience the lowest cavity losses and thus be the mode most likely to oscillate.

Figure 2 shows a plot of the minimum required RO injected power for locking as a function of unstable resonayor cavity length, L. Two cycles of N_{eq} are seen to have the expected frequency.

The attainment of transform-limited bandwidth is accomplished by injecting an RO beam of sufficiently narrow bandwidth. This is greatly simplified by the fact that, under the above specified conditions, less than 1 W of RO power is sufficient for locking. Thus, it is possible to injection lock a high power flashlamp-pumped dye laser with an ultra-narrow bandwidth cw dye laser.[6] In the case of an XeF laser, we have demonstrated[10] transform-limited bandwidth injection locking with an Ar-ion laser as the RO. By using selectively reflecting optics, the Ar-ion laser was made to lase on the 3511 Å transition of the doubly ionized species. A Fabry-Perot etalon was used to select a single longitudinal mode from the Ar-ion laser. The result after injection locking was a 50-MHz bandwidth for the 20-ns pulse duration of the XeF laser.

It is interesting to note that the unstable resonator itself can be made to have relatively low sensitivity to its own longitudinal modes. This is due to the fact that the longitudinal-mode interference effects in an unstable resonator occur predominantly in the paraxial region. Thus the small hole in the rear optic causes a large reduction in the intensity of those effects.

Another advantage of injection locking for excimer lasers is a significant increase in laser output. This is attributed to the earlier buildup of laser oscillation (to a saturating intensity) since the oscillation can start from a level well above the noise, consequently less energy is lost to fluorescence in the early building period. Figure 3 compares the time histories of locked and unlocked pulses from a KrF laser.

Finally it should be pointed out that it is only possible to lock all of the PO output to the RO linewidth if the PO transition is homogeneously broadened and all the emission emanates from a common upper state. This is the case for most of the excimers. For discharge-pumped XeF, however, it is only possible to lock ~ 60% of the output[10] to the RO line since the XeF laser emission originates at several different, slowly coupled states. If the communication rate among those upper states were to be increased (say, by raising the temperature) a greater locking percentage could be achieved.

In conclusion, the implementation of relatively simple techniques can allow the experimenter with a modest budget and level of effort, to obtain a ultraviolet excimer source of very high quality. This should enable many more researchers to address their fields of interest in the ultraviolet.

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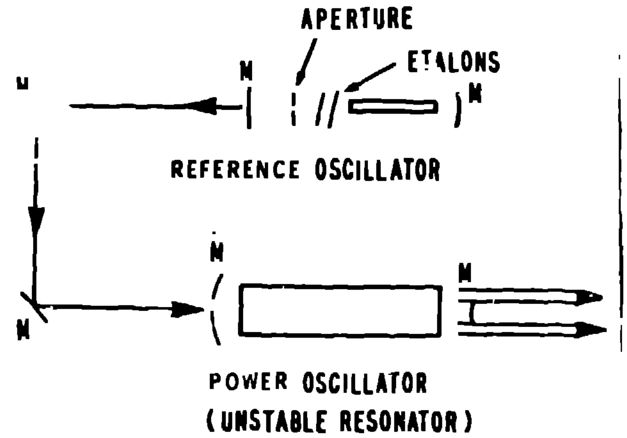

Figure 1

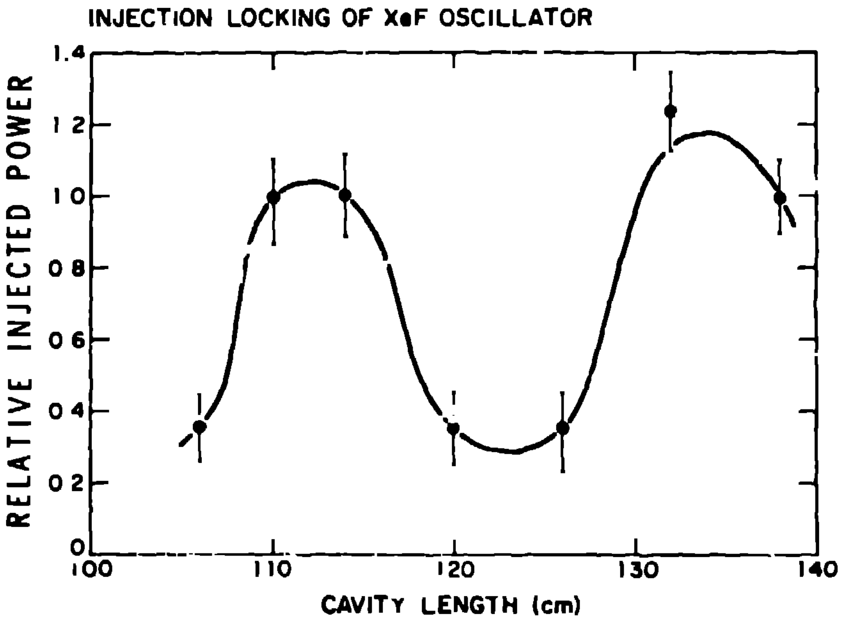

Figure 2

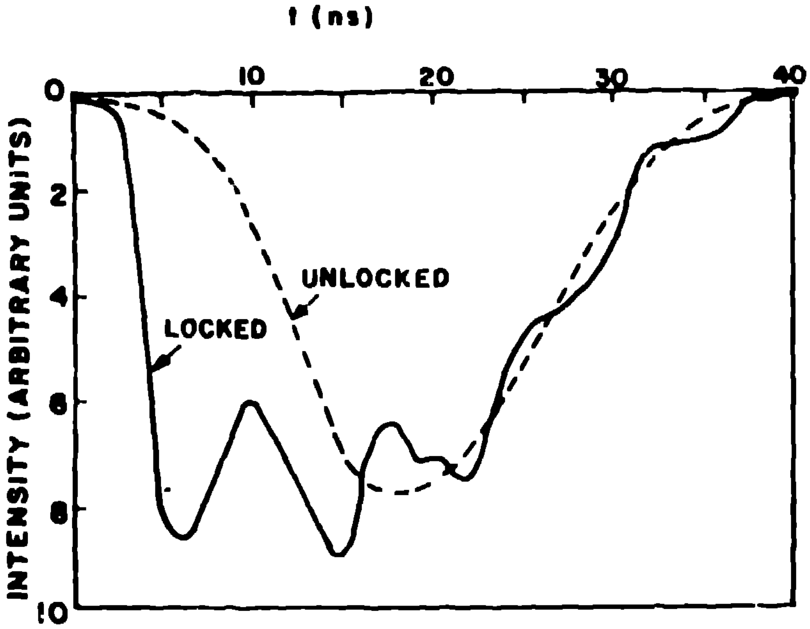

Figure 3