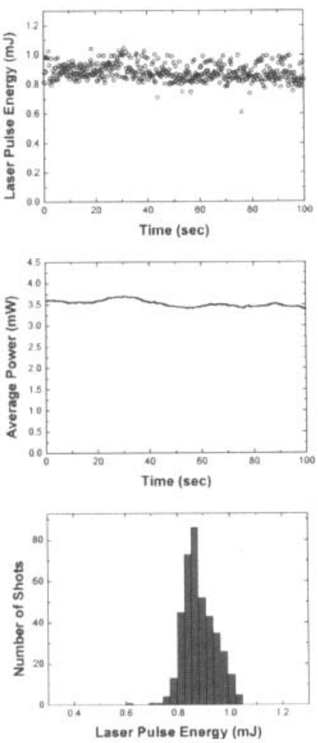
Generation of Milli-Joule-Level Soft X-ray Laser Pulses At 4Hz Repetition Rate in a Highly Saturated Tabletop Capillary Discharge Amplifier

C.D. Macchietto, B.R. Benware and J.J. Rocca

A characteristic that distinguishes soft x-ray lasers from other sources of coherent soft x-ray radiation is their potential to generate high-energy pulses. Soft x-ray lasers pumped by large optical lasers have produced output energies of up to several mJ. However, the laser facilities that produce these pulses are large and their repetition rate is limited to one shot every few minutes or less. In the past few years important progress has been achieved in the development of tabletop soft x-ray amplifiers that can fire at increased repetition rates.[1] In recent work we have demonstrated the generation of milli-Joule-level soft x-ray laser pulses at 4Hz repetition rate using a very compact tabletop device.[2] This result was obtained at a wavelength of 46.9nm by exciting Ne-like Ar ions in a capillary discharge plasma column 34.5 cm in length. Such large amplification length allows us to exceed by two to three times the gain-length product necessary to achieve gain saturation. Operation in this highly gain-saturated amplification regime permits efficient extraction of the energy stored in the population inversion from the majority of the amplifier volume.

The setup was similar to that used in our previous experiments.[3] The excitation current pulse was produced by discharging a water capacitor through a spark gap switch connected in series with the capillary load. The capillary discharge-pumped laser used in this experiment occupies an area of approximately 0.4m x 1m on top of a table, a size comparable to that of many widely utilized visible or ultraviolet gas lasers. Figure 1 shows the measured laser output pulse energy and average power. Laser pulses with an average energy of 0.88mJ (>2x10[14] photons/pulse) were generated at a repetition frequency of 4Hz, while the energy of the most intense pulses exceeded 1mJ. The average power obtained was 3.5mW, the highest reported to date for a tabletop soft x-ray laser. The laser pulses were measured to have a FWHM duration of about 1.5ns, and an average peak power of ≈0.6MW. The laser intensity at the output of the capillary exceeds the saturation intensity[4] by more than an order of magnitude, approaching 1GW/cm^2. The far field beam profile has a ring shape that is the result of refraction of the rays by plasma density gradients in the plasma column. The peak to peak divergence was measured at 4.6mrad. With its peak spectral brightness of ≈1x10^{23} photons/(s mm^2 mrad^2 0.01% bandwidth), this tabletop laser is one of the brightest soft x-ray sources to date.



Macchietto Figure 1. Measured laser output pulse energy and average output power at a repetition rate of 4Hz. **(a)** Shot to shot laser output pulse energy. **(b)** Average output power computed as a walking average of 60 contiguous laser pulses. **(c)** Distribution of the output pulse energy.

Acknowledgments

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References

1. "Short wavelength lasers and applications III," J.J. Rocca and L.B. Da Silva, eds., *SPIE*, **3776** (1999).
2. C.D. Macchietto, *et al.*, "Generation of milli-Joule-level soft x-ray laser pulses at 4Hz repetition rate in a highly saturated table-top capillary discharge amplifier," *Opt. Lett.*, **24**, 1115 (1999).
3. B.R. Benware, *et al.*, "Demonstration of a high average power tabletop soft x-ray laser," *Phys. Rev. Lett.*, **81**, 5804 (1998).
4. J.J. Rocca, *et al.*, "Energy extraction and achievement of the saturation limit in a discharge pumped table-top soft x-ray laser," *Phys. Rev. Lett.*, **77**, 1476 (1996).

High Power Single Mode Laser Operation With Intracavity Phase Elements

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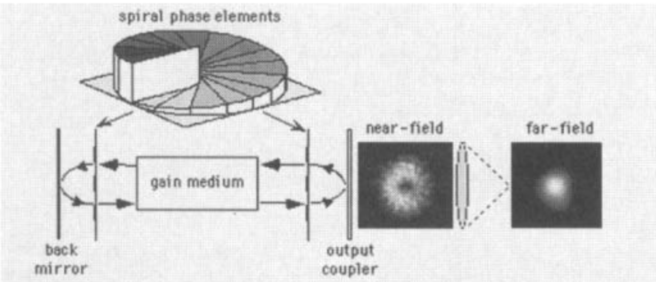
In a laser operating with many transverse modes, the output power is relatively high but the emerging output beam quality is inherently poor. Generally, improvement of the beam quality is achieved by inserting an aperture inside the resonator to reduce the number of modes. The size of the aperture can be decreased until only the optimal fundamental TEM_{00} mode of Gaussian shape exists. Unfortunately, this leads to a significant reduction of the output power, since only a small volume of the gain medium is exploited.

We have recently developed a novel method in which a single, high order mode operation, rather than low order mode operation, can be obtained. It is based on the insertion into the laser resonator of either discontinuous phase elements,[1] or continuous phase elements of spiral shapes.[2] The phase elements are designed to have sharp phase discontinuities where the desired modes have low intensity. Thus, they introduce very low losses to the desired modes, but high losses to other modes, especially to the fundamental mode. This leads to very high mode discrimination, with the possibility of obtaining a single, well-defined and stable high order mode operation. The high order modes have a wider intensity distribution than the fundamental mode, so they can exploit more of the gain medium, and thereby obtain relatively high output powers. Moreover, the elements have no radial dependence, so they are insensitive to axial displacement or thermal lensing.

The phase elements were fabricated with advanced photo-lithographic and etching techniques, so as to obtain very low scattering and losses of less than 0.25%. These were inserted into both Nd:YAG and CO_2 lasers, and experimentally evaluated to determine the power and quality of the output beams from the lasers. Figure 1 shows a typical laser configuration with the phase elements and representative results from a CO_2 laser with spiral phase elements designed to select the TEM_{01^*} mode. As shown, the near field intensity distribution of the TEM_{01^*} mode has the expected ring-like shape. Yet, the far field is focused into a diffraction-limited spot, which clearly indicates that the output beam is a pure high quality single mode. Typically, the measured output powers of 3 to 5 Watts from the lasers, operating at a single high order mode with our phase elements, were higher by 50% than when operating at the single fundamental mode. Although our experiments were conducted with only Nd:YAG and CO_2 lasers, the method is generic and could be used with many other lasers.

References

1. R. Oron, *et al.*, "Discontinuous phase elements for transverse mode selection in laser resonators," *Appl. Phys. Lett.*, **74**, 1373 (1999).
2. R. Oron, *et al.* "Laser mode discrimination with intra-cavity spiral phase elements," *Opt. Commun.*, **169**, 115 (1999).



Oron Figure 1. Typical laser configuration with spiral phase elements designed to select the TEM_{01^*} mode, along with the experimental near-field and far-field intensity distributions that emerge from a CO_2 laser.

Microcavities

Excitation Localization Principle For Whispering-Gallery Mode Microcavities

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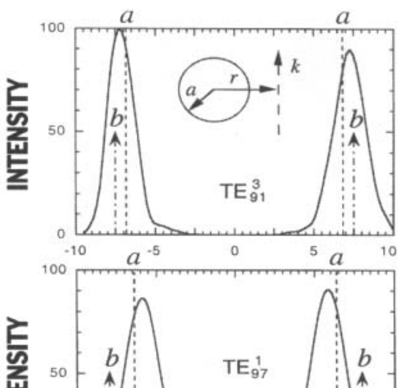
There is interest in utilizing whispering gallery mode (WGM) microcavities for photonic applications[1] (e.g., signal processing and environmental sensing) as well as in fundamental physics studies (e.g., cavity *QED*). These symmetric structures (e.g., spheres and disks) are relatively easy to fabricate yet display cavity *Q*s far surpassing those of similar sized Fabry-Perot resonators. The exceptional *Q*s result from near total internal reflection of circulating waves and are limited only by minimal photon tunneling through the curved interface. Theory[2,3] predicts that the optimum coupling of a tightly focused Gaussian light beam to a spherical WGM resonance of mode number, n, occurs when the beam is positioned *outside* the cavity at a distance, $b = (n + 1/2)\lambda/2\pi$. This simple proportionality has been called the van de Hulst localization principle[3] (LP).

Although the validity of LP had been universally accepted based on past successes of Lorenz-Mie theory, the concept had not been rigorously experimentally tested. Recently,[4] however, we explored its limits using liquid droplets and glass spheres. We found that LP and experiment roughly agreed only in those cases involving relatively low Q modes, when the microsphere could be considered ideal. However, when surface perturbations limited realizable *Q*s, as in the case of the near-surface highest n highest Q modes, LP failed. Somewhat surprisingly, we find that these resonant modes are still efficiently excited through a non-photon tunneling channel involving surface scattering. This channel is optimized when the beam excites a region slightly within the edge of the sphere. This is illustrated in the upper two panels of Figure 1, summarizing droplet lasing experiments. In these, a 2.5 µm excitation beam is equatorially scanned through 6.6 ± 0.2 µm radius water droplets containing laser dye. Plotted are the beam position r and the resulting lasing intensity. The vertical dashed line represents the droplet surface ($r = a$). When the mode Q is about 10^4 (upper panel), optimum lasing indeed occurs when the excitation beam is positioned near the calculated b. The 0.25 µm difference between b and observation was consistent with the finite size of the beam, the b value being strictly true only in the zero-size limit.[4,5] The middle panel of Figure 1 contrasts a high Q ($\approx 10^8$) mode showing that lasing occurs best when the beam is aimed slightly inside the sphere's rim, in contradiction to LP.

To understand the failure of the localization principle, we numerically modeled[4,5] the high Q case (see lower panel of Figure 1) assuming that the droplet surface had a fractional ripple of amplitude ϵ. In the limit $\epsilon \rightarrow 0$, the peak position occurs at b, as expected. However, as ϵ is increased, the optimal position shifts within the droplet, as observed.



Lin Figure 1. Upper two panels are plots of observed lasing intensity versus beam position for 6.79 and 6.43 µm radius water droplets, respectively. The upper panel shows expected "localization" behavior for a relatively low Q case ($Q = 10^4$), while the middle panel illustrates non-localized behavior for a high Q case ($Q \approx 10^8$). The lower panel is calculated from theory and shows that a molecular scale surface perturbation ϵ accounts for the high Q non-localized behavior.