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Superfluorescent generation of mode-locked π pulses

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Swept gain superfluorescent operation is reported in a mode-locked laser. We quantitatively compare theoretical predictions and experimental results for the laser output, which show drastically reduced pulse lengths together with increased bandwidth corresponding to the generation of near-π pulses. The attainment of this operating mode depends on the intracavity power level and the relevant homogeneous lifetimes. The effect has been observed for several mode-locked argon laser lines.

We report on the theory and experimental observation of a new type of mode-locked laser operation. Traditional types of mode-locked laser produce pulses whose minimum pulse width is of the order of, or greater than, the inverse of the gain bandwidth. Pulses considerably shorter than this are, however, known to be generated in superfluorescence. We have now combined the superfluorescent coherent pulse shortening phenomenon, with mode-locking techniques, to generate short, intense pulses with an area approaching π. In our mode-locked argon-ion laser experiments, this has resulted in pulse lengths roughly three times shorter than those normally observed. Our method appears to provide a universal technique for reducing the pulse length of mode-locked lasers below the apparent limit given by the small-signal-gain bandwidth.

The theory of superfluorescence initially treated point samples in single-mode cavities.[1] Later developments treated superfluorescence in extended systems,[2-4] and emphasized the relative time scales involved. In order to have true superfluorescence, is is necessary that $\tau \ll T_2^* \ll T_1, T_2'$ where $\tau = T_2/\alpha_0 L$ is the superfluorescence time. It is clear that true superfluorescence is only obtained for overall gains much greater than unity, i.e., $\alpha_0 L \gg 1$. Here T_2^* is the Doppler-induced dipole dephasing time; T_1, T_2' are the longitudinal and transverse decay times; while α_0 is the small-signal gain in the gain medium of length L. In many laser systems, especially in the visible region, it is difficult to obtain $\alpha_0 L > 1$ in a single pass, which means that conventional superfluorescence is impossible.

In our work, the effective gain length is extended and effectively swept through the medium using a mode locker and high-reflectivity mirror to return the output to the cavity repeatedly. This allows us to obtain superfluorescence even in relatively small lengths, with a steady-state or mode-locked output. Active mode locking is generally achieved in combination with a relatively lossy output coupler, and due to the high losses, no true superfluorescence is obtained. Thus the output bandwidth of a mode-locked laser is usually regarded as limited by the small-signal-gain bandwidth $(T_2^*)^{-1}$ rather than by τ^{-1}. To overcome this problem we have simply increased the cavity Q factor in a mode-locked laser until the effective length [i.e., (cavity length)×(number of round trips)] greatly exceeds $1/\alpha_0$. Defining the effective length L' as $2L/A$ for an overall round trip absorption of A, the superfluorescence criterion then becomes $\alpha_0 L \gg A/2$. We also require that $T_p \ll T_R$ in order that the inverted atoms can reequilibrate with the pumping mechanism with time scale T_p between round trips, which take a time T_R. These criteria are easily achieved in an argon-ion laser,[5] allowing us to observe superfluorescence for the first time in several visible lines of the Ar^+ ion. The resulting superfluorescent pulse train is characterized by pulses having a width significantly shorter than the dephasing time T_2.

The chief new feature that is required in understanding mode-locked superfluorescence is the effect of the mode locker. In a uniform gain superfluorescent system, it is necessary to have $L < L_{\mathrm{AC}}$ where L_{AC} is the Arecchi-Courtens cooperation length,[6] in order to prevent the breakup of the medium into independently emitting regions of length L_{AC}. This criterion is not satisfied in a normal argon laser. In fact, without the mode locker, the output is just that of an incoherent multimode continuous-wave laser. However, the mode locker and high reflector together generate a high reflectivity in a periodic time window, which is synchronized with the cavity round-trip period. This selects only those coherent phase-locked amplitudes which can produce output during the time window. The propagating pulse therefore experiences a swept gain which effectively suppresses counterpropagating or independently triggered (nonsynchronous) pulses. We model this mode-locked system numerically by combining the standard superfluorescence propagation equations with a time-dependent absorber at the mode-locker location.

We find that the results of the numerical simulations are remarkably similar to those for ordinary superfluorescence, in terms of the predicted pulse structure. We attribute this to the relatively slow change in time of the transmission of the mode locker, with a period over 100 times longer than the superfluorescence time scale τ. Since the mode locker has little apparent effect on the pulse structure, we view the high-Q mode-locking technique as an effective way of obtaining true π-pulse propagation in an amplifier. The π-pulse limit is the steady-state limit of superfluorescence, when the gain balances the loss.

The equipment used in the experimental studies consisted of a small frame argon-ion laser (Spectra Physics model 165) in an extended cavity configuration mode locked by a Coherent (model 467) mode locker. A 3.8% output coupler was mounted close to an inclined fused silica plate which could be rotated over a range of angles close to Brewster's angle to provide a variable loss output coupler. The oscillating bandwidth of the mode-locked laser was measured using a 30-GHz free spectral range, scanning, confocal Fabry-Pérot interferometer (Coherent model 240). The pulse durations were measured using background-free (noncollinear) autocorrelation with a β-barium borate crystal cut at 53°, and have been corroborated by measurements performed with a streak camera and by cross correlation with pulses from a synchronously pumped dye laser. The distinctive features of the output from this laser at high intracavity powers (notably the significantly increased bandwidth and shortened pulses) have already been reported for the case when the laser was operated in a cavity-dumped mode-locked configuration.[7] In this configuration it appeared initially that the cavity dumper was responsible for the new features of the laser pulses, but we have recently been able to obtain similar results with a simple linear cavity. Measurements on this system, and also on a large frame argon laser, have shown that the bandwidth enhancement is primarily a function of the intracavity power (see Fig. 1). This result is consistent with the results of the numerical simulations. In order to compare the calculations with the experimental results, the small signal gain per pass of this laser was measured by adjusting the variable loss output coupler to threshold during non-mode-locked operation of the laser. For the 514.5-nm line we obtained a value of 0.36 for the gain per pass at a plasma current of 35 A. Here a pass is defined as one round trip through the resonator involving a total distance of about 4 m (with a total active length of about 1 m).

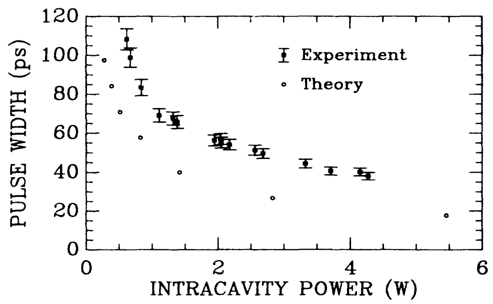

FIG. 1. Experimentally observed variation of argon laser pulse width (determined by autocorrelation assuming a Gaussian pulse shape) as a function of average mode-locked intracavity power compared with the results of the numerical simulations. The intracavity power was varied either by varying the plasma current or output coupling loss. For details of the experimental configuration see text.

We have also investigated mode-locked operation of the laser at other frequencies, and in all cases have found similar qualitative effects. In the case of the 488-nm line, the enhanced bandwidth and shorter pulses are obtained at much lower intracavity powers. It has only been possible to mode lock the 488-nm line at lower plasma currents (≤ 17 A) due to its much higher small signal gain, but the observation of superfluorescence pulses at lower intensities is consistent with the much larger transition probability for this line.

Our propagation equations are the usual ones assumed for coherent pulse propagation in the plane-wave approximation.[8] Due to the presence of the mode locker, only one-directional pulses can evolve. Thus we have for the Rabi frequency Ω of the field, detuned polarization $P(\Delta)$, and inversion $D(\Delta)$,

$$\begin{aligned}\frac{\partial\Omega}{\partial x}&=g\int\rho(\Delta)P(\Delta)d\Delta\ ,\\ \frac{\partial P(\Delta)}{\partial t}&=-(\gamma_2'+i\Delta)P(\Delta)+\Omega D(\Delta)\ ,\\ \frac{\partial D(\Delta)}{\partial t}&=-\gamma_p[D(\Delta)-1]-\mathrm{Re}[\Omega^*P(\Delta)]\ .\end{aligned}\tag{1}$$

Here x and t are space and time coordinates comoving with the pulse, γ_p is the pumping rate, γ_2' is the homogeneous damping rate of the atomic polarization, $g=\alpha_0/2T_2^*$ is the inhomogeneous gain coefficient, and $\rho(\Delta)$ describes the distribution of atoms in the medium detuned from the resonant frequency by Δ. The argon medium is predominantly inhomogeneously broadened by the high-temperature Maxwell distribution of atomic velocities. Hence $\rho(\Delta)$ is taken to be a normalized Gaussian with an experimentally observed cw linewidth of 6.6 GHz (full width at half maximum). This includes a contribution due to Zeeman splitting resulting from an applied axial magnetic field, present to reduce losses incurred at the surface of the tube enclosing the gain medium. The Zeeman splitting was not taken into account explicitly in the simulations other than in its contribution to the total inhomogeneous linewidth. In terms of the lifetimes[8]

$$T_2\cong T_2^*\equiv\pi\rho(0)\ .\tag{2}$$

With $T_2'=(\gamma_2')^{-1}$ denoting the homogeneous and T_2^* the inhomogeneous lifetime contributions to T_2, we have

$$T_2^*\sim 71\ \text{ps},\quad T_2'\sim 640\ \text{ps}\ .\tag{3}$$

Using these lifetimes the aim of the simulations is to generate steady-state pulse profiles for comparison with experiment in the case when a low loss output coupler results in high intracavity power. Our model for the pumping as a two-level process is approximate. However, due to the short time scales of the pulses (~ 40 ps), this is irrelevant, as the pumping time scales are ≥ 1 ns. We used 5 ns in the simulations, which is intermediate between the upper-level relaxation time of ~ 7 ns and lower-level relaxation time of ~ 0.36 ns (Ref. 5).

Propagation of the coupled atom-field equations is achieved using a standard numerical procedure.[9] An initial low amplitude seed pulse is allowed to develop under the action of the equations (1). Upon entering the gain region the polarization and the inversion are assumed to have equilibrated with the pumping mechanism (continuous discharge) so that $P(\Delta)=0$ and $D(\Delta)=1$. After traveling a distance L, the resulting electric field amplitude is subjected to a time-independent transmission of $(1-A)^{1/2}$ which models the output coupler. After traveling a further distance L in the gain medium, the amplitude is subjected to a time-dependent loss which models the mode locker. The amplitude transmission function used in the calculations for the mode locker was

$$a(t)=1-\alpha\sin^2(\omega_m t)\ . \tag{4}$$

Here α determines the diffraction efficiency through the acousto-optical mode locker, in our case, $\alpha=0.2$, and the frequency $\omega_m=\pi/T_R$. Thus the zero loss transmission occurs periodically with a time interval equal to the round-trip time T_R. The calculation is repeated until a stable pulse is obtained.

Typical numerical and experimental results for the pulse width as a function of intracavity power are shown in Fig. 1. In addition, Fig. 2 shows the development of the numerically computed pulse areas, for different intracavity losses. The pulse area, as usually defined by

$$\Theta(x)=\int_{-\infty}^{+\infty}\Omega(x,t)dt\ , \tag{5}$$

rapidly assumes an asymptotic value in the region of (but less than) π. The pulse area generated in the simulations for an output coupling of $A=0.038$ corresponds to approximately 95% of (initially upper-level) atoms returned to the lower state upon passage of the pulse, while a true π pulse would totally invert the populations of the two levels.

The qualitative features of the variation of the pulse widths and bandwidths with intracavity power are fully reproduced by the simulations, but the numerically computed parameters show more dramatic effects for a given intracavity power than are observed experimentally. The discrepancy between theory and experiment is reasonable however, given that the transverse nature of the field has been neglected. Semiclassical calculations[10] and fully quantized calculations[11] including transverse fields and diffraction in superfluorescence have demonstrated longer pulse lengths than plane-wave calculations. This result is compatible with our experimental results. Initial simulations neglecting the inhomogeneous broadening, and ascribing the 6.6-GHz linewidth to homogeneous broadening, generated qualitatively similar results for the bandwidth and pulse width of the mode-locked laser.

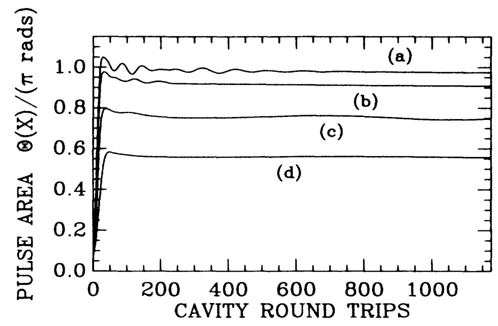

FIG. 2. Variation of the pulse area as a function of output coupling loss, and number of passes through the resonator, showing the approach to π pulses. The output couplings used in these simulations were (a) 1%, (b) 3.8%, (c) 11.1%, (d) 20%.

In conclusion, we report the mode-locked operation of an argon laser at high intracavity powers. The output pulses agree with the results of simulations including the mode locker and are remarkably similar to those predicted in the experimentally inaccessible long path limit of superfluorescent pulse propagation at this wavelength. We note that although earlier authors have suggested this possibility,[12] our results appear to be the first observations of mode-locked coherently produced sub-T_2 pulses. There are many applications for the increased peak power and decreased pulse length of these pulses. In addition, the operation of the laser in this regime opens up new possibilities for the study of superfluorescent pulse propagation. It is likely that similar effects will occur universally in the short pulse limit, in other mode-locked laser systems.

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