$P/P_C(\eta=1)\approx 0.4$, before the transition, (B) $P/P_C(\eta=1)\approx 0.8$, just after the condensation of $\eta=1/2$, and (C) $P/P_C(\eta=1)\approx 1.95$, when the peak power of $\eta=2$ starts to increase. In the first row (A), the laser still works in a noisy regime for all η, and the light waveforms show modulated noise that approximately follows the applied modulation signals, each with its respective η, but not mode-locking. The second row (B) shows the condensate waveforms for $\eta=1/2$, and the non-condensate waveforms for $\eta=1,2,4$ with a gradual population buildup. The third row (C) shows the pulses obtained for all three cases at a high power level, but clearly shows the much better quality of the pulses for $\eta=1/2,1$ compared to the $\eta=2,4$ cases. We can therefore summarize that when condensation takes over the pulses drastically shorten from noise waveform widths in the order of the cavity length down to ~1 ns)and in shorter lasers and reduced jitter to less than ps), corresponding to the lower eigenmode that depends on η. Since harmonic modulation ($\eta=2$), the common and simple method used for active mode locking, is at the boundary of condensation, it is a less effective way to generate short pulses compared to the nonsmooth modulations with $\eta<2$.

We add a note on condensation of light in mode locked lasers at dimensions higher than one. Theoretically, if the $t=x/(c/n)$ dependent operator $\widehat{O}(t)$ in Eq. (1) is extended to 2 or 3 dimensions, i.e. $\widehat{O}(\vec{r})=\left(\gamma_g-i\gamma_d\right)\nabla^2-V(\vec{r})$, the analysis gives weaker conditions on the potential (modulation) exponent, η, required for condensation. For example, in three dimensions, condensation occurs for all values of η, including the zero potential case where the system has only a volume confinement. For observing condensation in three dimensions we can use for example a laser cavity with many transverse modes instead of a single mode fiber. Under the paraxial approximation, Eq. (1) holds with

$$\widehat{O}(t,y,z)=\left(\gamma_g-i\gamma_d\right)\frac{\partial^2}{\partial t^2}+\left(\gamma_1+i\gamma_2\right)\nabla_\perp^2-V_x(t)-V_\perp(y,z)\,, \tag{4}$$

where $t=x/(c/n)$ is the propagation direction (in the pulse frame), and y,z are the transverse directions. The $i\gamma_2\nabla_\perp^2$ term naturally originates from the paraxial approximation, whereas $\gamma_1\nabla_\perp^2$ can result from spectral filtering in the transverse spatial frequencies. $V_\perp(y,z)$ is an optional loss potential in the transverse direction, while $V_x(t)$ is the modulation potential. We can think of three-dimensional experimental realization by using a perfectly coated cylindrical cavity, a gain medium with current modulation, and two loss masks: one that introduces a modulated loss $V_\perp(y,z)$ at the transverse directions, and the second mask with matching lenses provide spatial filtering. According to the theory, for any applied modulation signal $V_x(t)$, the laser should produce a condensate waveform, beyond a threshold pumping level, where the first transverse mode and the lowest pulse mode occupy a macroscopic portion of the power.

Conclusion

We have experimentally demonstrated Bose-Einstein condensation in active mode-locking. Besides the basic side in being a new one dimensional laser light BEC system, it can have practical meanings for ways to use modulations that can be more effective than the usual methods for producing high quality short laser light pulses.

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