High efficiency and low noise amplification of ultrashort pulses by quasi-parametric amplification

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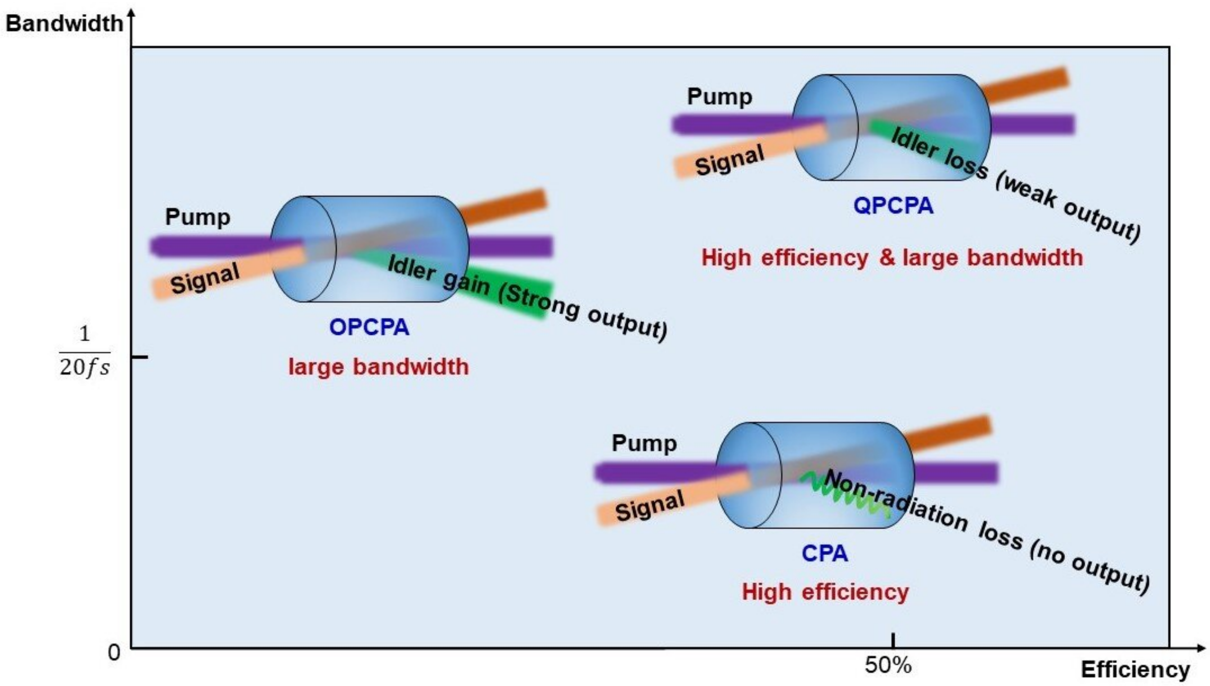


In CPA, the pump amplifies the signal through an energy-level gain medium system in which one of the transitions is non-radiative. This kind of laser amplification has a high efficiency from the pump to signal and a relatively narrow gain bandwidth. In OPCPA, the pump amplifies the signal through parametric interaction and simultaneously generates the idler wave. OPCPA can be broadband by manipulating the phase-matching condition but suffers from a relatively low efficiency due to back conversion. QPCPA is a variation of OPCPA by dissipating the idler with strong crystal absorption. The idler dissipation obstructs the back conversion effect and enables both high efficiency and large bandwidth. Credit: Jingui Ma et al

Since the earliest demonstration of chirped-pulse amplification (CPA) and optical parametric chirped-pulse amplification (OPCPA), femtosecond lasers have been able to deliver ultrahigh peak powers up to ten-petawatt (PW), thereby paving the way for compact particle accelerators and X-ray sources.

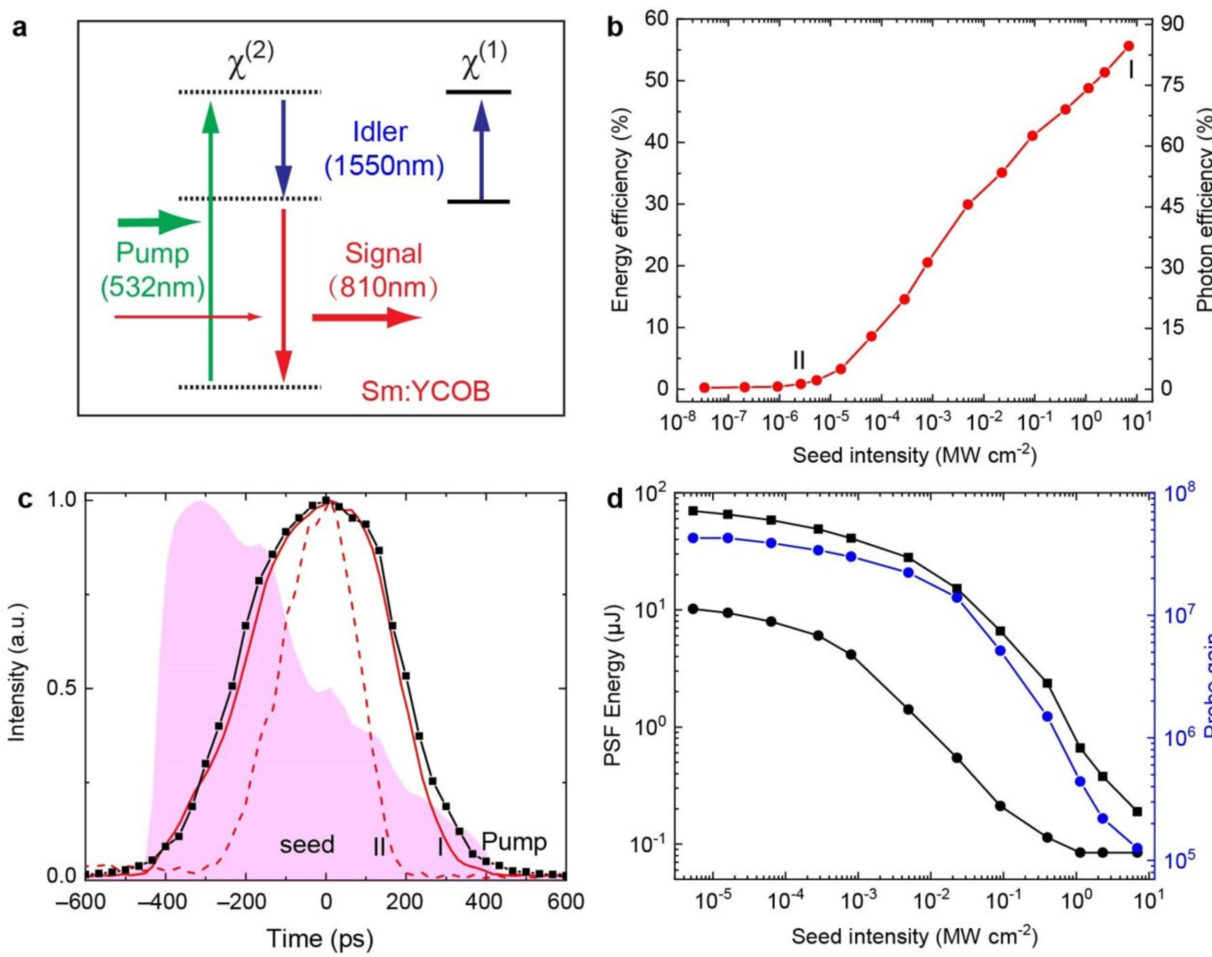
To further increase peak powers, laser amplification schemes with both high conversion efficiency and large bandwidth are needed. However, CPA laser amplifiers suffer from relatively narrow gain bandwidth, whereas OPCPAs suffer from relatively low signal efficiency or pump depletion due to back conversion.

In a new paper published in *Light: Science & Applications*, a team of scientists, led by Professor Liejia Qian from Key Laboratory for Laser Plasmas (MOE), School of Physics and Astronomy, Shanghai Jiao Tong University, China, and co-workers have demonstrated an ultrahigh-efficiency and low-noise scheme of quasi-parametric chirped-pulse amplification (QPCPA), which is a variation of OPCPA by dissipating the idler with strong crystal absorption.

The idler dissipation obstructs the back conversion effect and enables the QPCPA performance of high efficiency, large bandwidth, and robustness against phase mismatch. They experimentally demonstrated 56% energy efficiency for an 810-nm signal converted from a 532-nm pump, or equivalently 85% pump depletion. Such a record high depletion greatly suppressed the parametric superfluorescence (PSF) noise in QPCPA to only ~10^{-6} relative to the amplified signal energy.

In their experiment, a 8-cm Sm:YCOB crystal was used with the orientation for maximized nonlinear coefficient, which was transparent for both the pump and signal but opaque for the idler. Under a pump intensity of 3 GW cm^{-2}, the highest signal efficiency of 56% was achieved with a seed intensity of ~7 MW cm^{-2}, corresponding to a pump depletion of 85%.

The demonstrated QPCPA pump depletion was approximately 2.5 times that of OPCPA. The strong pump depletion by efficient signal amplification significantly suppressed the generation of PSF noise. Within the largest signal output of ~65 mJ, the measured PSF noise energy was as low as ~10 μJ. The pulse contrast after compression should be as high as ~10^9.



a, Schematic of QPCPA scheme. The pump at 532 nm amplifies the signal at 810 nm and simultaneously generates the idler at 1550 nm. The generated idler has an absorption by the doped rare-earth ions Sm^{3+}. b, Pump-to-signal efficiency and pump depletion versus seed intensity under a pump intensity of ~3 GW cm^{-2}. c, Pulse profiles of the pump (black), amplified signal at seed intensities of 7 MW cm^{-2} (red solid, point I marked in b) and 2.5 W cm^{-2} (red dashed, point II marked in b). The shaded area shows the chirped-pulse profile (spectrum) of the signal seed. The signal chirp is 40 ps nm^{-1}. d, Evolution of the parametric superfluoresecence (PSF) energy (black squares and circles) and probed small-signal gain (blue circles). Credit: Jingui Ma et al

Prof. Ma, the first author, explained why they named such a process "quasi-parametric" amplification: "The QPCPA process is very interesting. In the saturated amplification regime, its efficiency keeps increasing with the seed intensity without any back conversion, quite similar as 'non-parametric' laser amplification. However, in the small-signal amplification regime, it inherits all the parametric behaviors of OPCPA. The QPCPA combines the merits of parametric and non-parametric processes."

"Since the back-conversion effect is completely obstructed, the QPCPA is also robust against phase mismatch. This means that QPCPA is insensitive to the variation of pump beam pointing and the environment temperature. This benefits the high repetition-rate operation of QPCPA," he added.

"With its very large product of efficiency and bandwidth, the QPCPA scheme based on a large-size Sm:YCOB crystal can support a peak power as high as 50 PW by using the same pump energy of current ten-petawatt laser facilities, so QPCPA may be a qualified candidate for pushing ultraintense lasers beyond the current ten-petawatt limit," Prof.

Ma said.

More information: Jingui Ma et al, Demonstration of 85% pump depletion and 10−6 noise content in quasi-parametric chirped-pulse amplification, *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00967-6

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