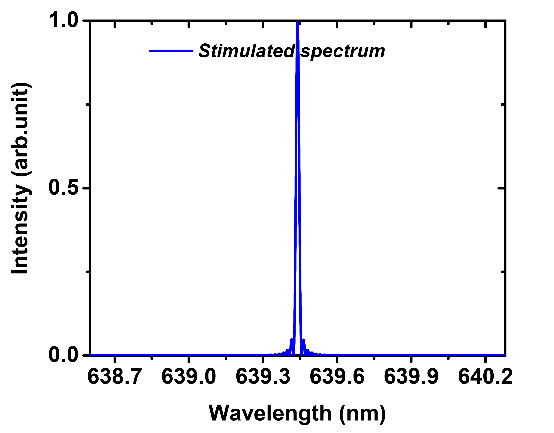
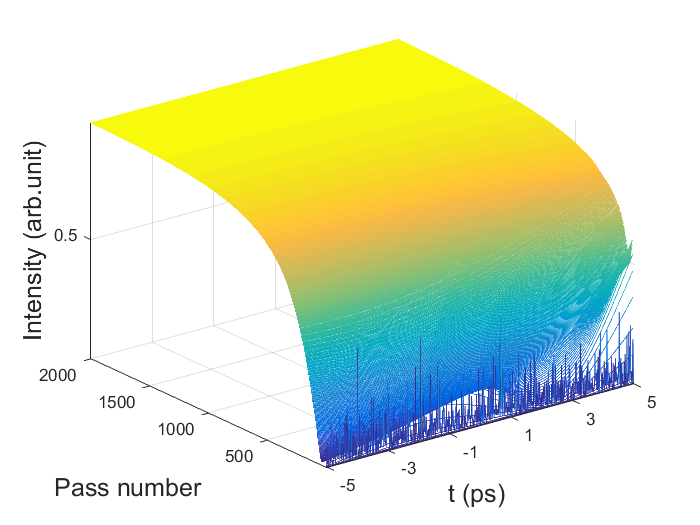


**(b)**

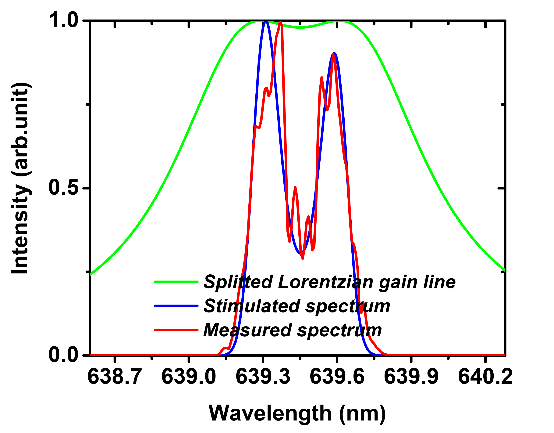
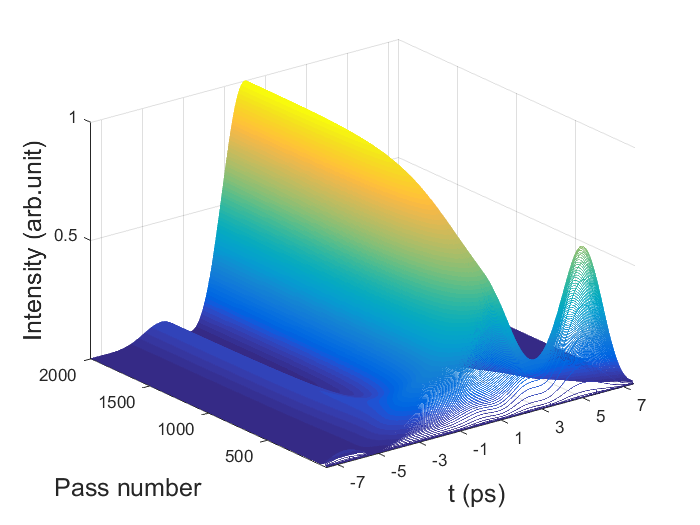
**(a)**



**(d)**

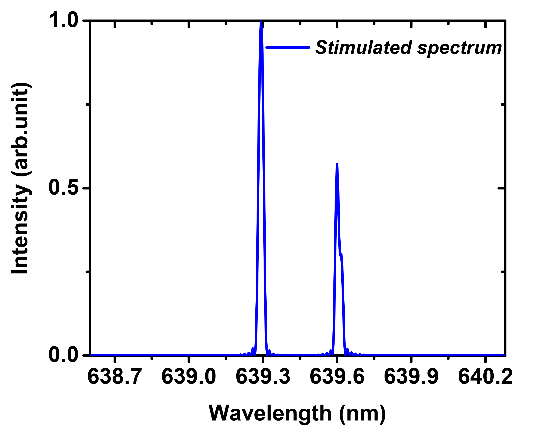
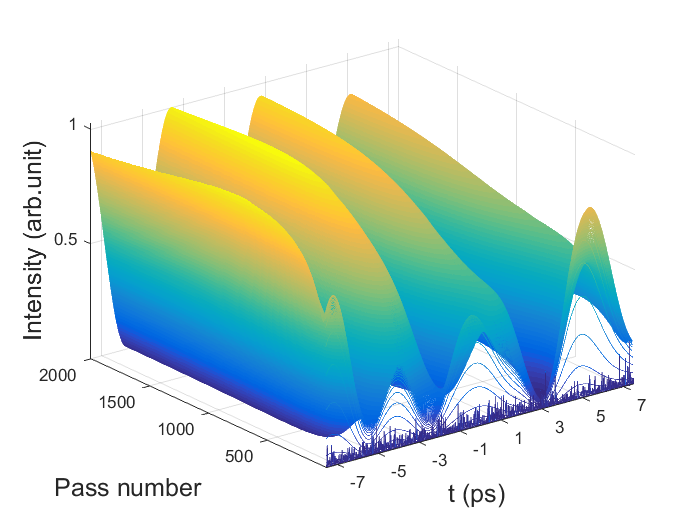
**(c)**

Fig 6. Simulated pulse evolution and final spectrum without frequency shift caused by gain line splitting. (a) and (b) are the situations with intensity modulation; (c) and (d) are situations without intensity modulation.



**(a)**

**(b)**



**(d)**

**(c)**

Fig 7. Simulated pulse evolution and final spectrum with frequency shift caused by gain line splitting. (a) and (b) are the situations with intensity modulation; (c) and (d) are situations without intensity modulation.

The model of the self-started Kerr-lens mode-locking procedure consists of a laser gain media and an intensity modulator. The laser gain media can be thought of as an amplifier that has a gain line shape, which can be modeled by a frequency filter. As for the amplifier, the saturation effect should also be taken into account and its effect on the gain factor *g* is given as

,(1)

Where *g*ss is the small-signal gain factor, *P* is the signal power, *P*sat is the saturation power. With regard to the gain line shape, Pr3+:YLF laser is solid-state laser with a gain-line shape corresponds to Lorentzian profile which belongs to homogeneous broadening [2016, Li Qing-Song]. The gain coefficient can be expressed as

,(2)

among which *ν*0 is the central frequency and *Δν* is Full Width at Half Maximum (FWHM) of the laser gain-line shape. For the 3P0→3F2 transition line at 640 nm, *Δλ* is 0.69 nm, leading to a *Δν* of 506.2 GHz. Owing to the spatial-temporal narrowing of the signal by Kerr-lensing effects of the gain media, the intensity of the intracavity laser is modulated passively. The model of the intensity modulation can be briefly thought of as a Gaussian profile in the time domain and be written as

,(3)

where *t*0 is the reference time, and *Δt* is the FWHM of the modulation signal.

After the laser crystal, the signal propagates in the atmosphere, where it experiences no chromatic dispersion or nonlinear effect, and is governed by the linear differential equation

,(4)

where *L* is the cavity round-trip loss, and can be solved by using the finite element method. After one round trip, the signal is fed in the gain media again and completes another round trip. The process is repeated until equilibrium is reached.

The simulation results that coincides with the FWHM of the measured spectrum depicted in Figure 6 (b), which was 0.39 nm, is depicted in Figure 6(a) and (b). In this simulation, the FWHM of the modulation signal *Δt* was tuned to 3.5 ps so that the FWHM of the calculated spectrum was also 0.39 nm. As is shown in Figure 6(a), a stable optical pulse was obtained with a pulse width of 1.5 ps, leading to a time-bandwidth product of 0.427, meaning a transform limited result. As a comparison, simulations with no intensity modulation was also carried out, the response in time domain and the simulated wavelength are illustrated in Figure 6(c) and (d), respectively. As can be seen, the result in the time domain becomes a direct current signal, and the FWHM of the simulated wavelength was shortened, corresponding to a continuous-wave operation state.

It is interesting to note that, in our experiments, meanwhile the laser was mode-locked, laser spectrums with a relatively big dip in the center shown as the red line in Figure 7(b) were sometimes captured. The possible reason for the dip in the laser spectrum is the frequency shift caused by gain-line splitting [93, Zhijiang Wang]. By introducing a frequency shift of the Stark splitting *Δνs* from the unperturbed frequency induced by the intra-cavity laser field, Eq. (2) can be written as

,(5)

By substituting Eq. (5) into the system instead of Eq. (2) and adjusting the frequency shift *Δνs* to 176 GHz (corresponding to a wavelength of 0.16 nm)and modulation duration in Eq. (3) to 45 ps, we can obtain a simulated spectrum almost identical to the registered one shown as the red line in Figure 7(b), with a FWHM of 0.39 nm. As shown in Figure 7(a), the FWHM of the corresponding optical pulse was 2.4 ps, resulting in a time-bandwidth product of 0.936. It should be noted that, to get the simulation results, the duration of intensity modulation model raised almost 13 times compared with the case without frequency shift resulted from gain line splitting, which reveals the fact that the stark shift has the effect of modulating intensity, or in another word, compressing optical pulses. This conclusion is consistent with the experimental results reported by J. J. Sanchez-Mondragon in 1986 [86, J. J. Sanchez-Mondragon].

The frequency shift of the gain line stark splitting was once considered as the cause of self-start mode locking [92, Zhijiang Wang]. As shown in the green line in Figure 7(b), the amount of frequency shift in our case (*Δνs* to 176 GHz, *Δν* of 506 GHz) already meets the requirements for the rough self-mode-locking criterion 12*Δνs*2 >*Δν*2 of solid-state lasers. For verification of the origin of self-start mode locking, we removed the intensity modulator and made the same simulation, the results are shown in Figure 7(c) and (d). As can be seen, frequency shift caused by gain line splitting would induce fluctuations of transient laser power in the time domain, but it alone cannot give rise to stable ultra-short pulses with a period of the cavity round-trip time without the help of intensity modulation, which might be caused by Kerr-lensing effect.

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