Soliton Pulse Generation in Kerr Resonators

Yinjuan Zhai, Zuxing Zhang and Zhiqiang Wang

Abstract

In theory, laser and fiber resonator can interact and generate frequency combs with a repetition frequency of FSR through Kerr nonlinear effect, enabling us to observe stable pulse waveforms with periodic reciprocal repetition frequency in the time domain, also known as optical solitons. Since the pulse width in the time domain is affected by the dispersion effect of the fiber, the intensity of the nonlinear effect and the frequency-locked detuning value, according to the nonlinear Schrodinger equation and the boundary conditions of the optical field transmission, we can obtain numeric value of the peak power of solitons in the cavity varying with driving power and detuning value using Matlab to scan driving power and detuning value. By doing numerical simulation, we can find optimal driving power and detuning value within the allowable power range of the laser to reduce the width of the cavity pulse and increase the peak power of the pulse. Experimentally, because the optical fiber cavity is affected by ambient noise, ambient temperature, and frequency stability of the driving light source, the time domain waveform will constantly drift, so it is difficult to observe the stable waveform solitons. Here, we use PID (proportional-integral-differential) feedback circuit to lock the CW laser frequency to the reference frequency of the resonator, and design a box used to insulate the cavity to suppress the waveform drift caused by temperature instability.

Numerical Model

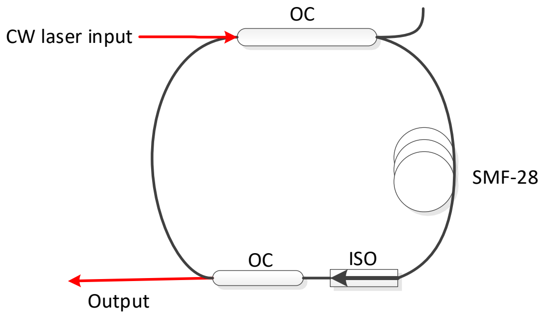

Fig. 1. CW laser transmitting through an optical fiber cavity.

The fiber cavity consists the fiber sections, a drive source, and losses from both the fiber and the fiber components. Numerically, the fiber sections are modeled by a nonlinear Schrodinger equation including loss, second and third order dispersion, Kerr nonlinearity, and detuning given by

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A + i\delta A \tag{1}$$

where A is the slowly varying envelope of the electric field, α is loss per unit length, δ is detuning per unit length, β_2 is group-velocity dispersion, γ is the nonlinearity coefficient, and a single polarization state is assumed. The fiber section is implemented with the standard split-step Fourier technique with the dispersive effects calculated in the Fourier domain and the nonlinear effects solved with a 4th order Runge-Kutta method.

The periodic boundary conditions are modeled using

$$A^{n+1}(0,t) = \sqrt{TD} + A^{n}e^{-\alpha_0} \tag{2}$$

where n represents the round trip number, D is the drive power per roundtrip, T is the input coupling coefficient, and α_0 is the total additional length independent component loss per roundtrip[1] .

Results of numerical simulation

Cavity optical field varying with detuning exclusively

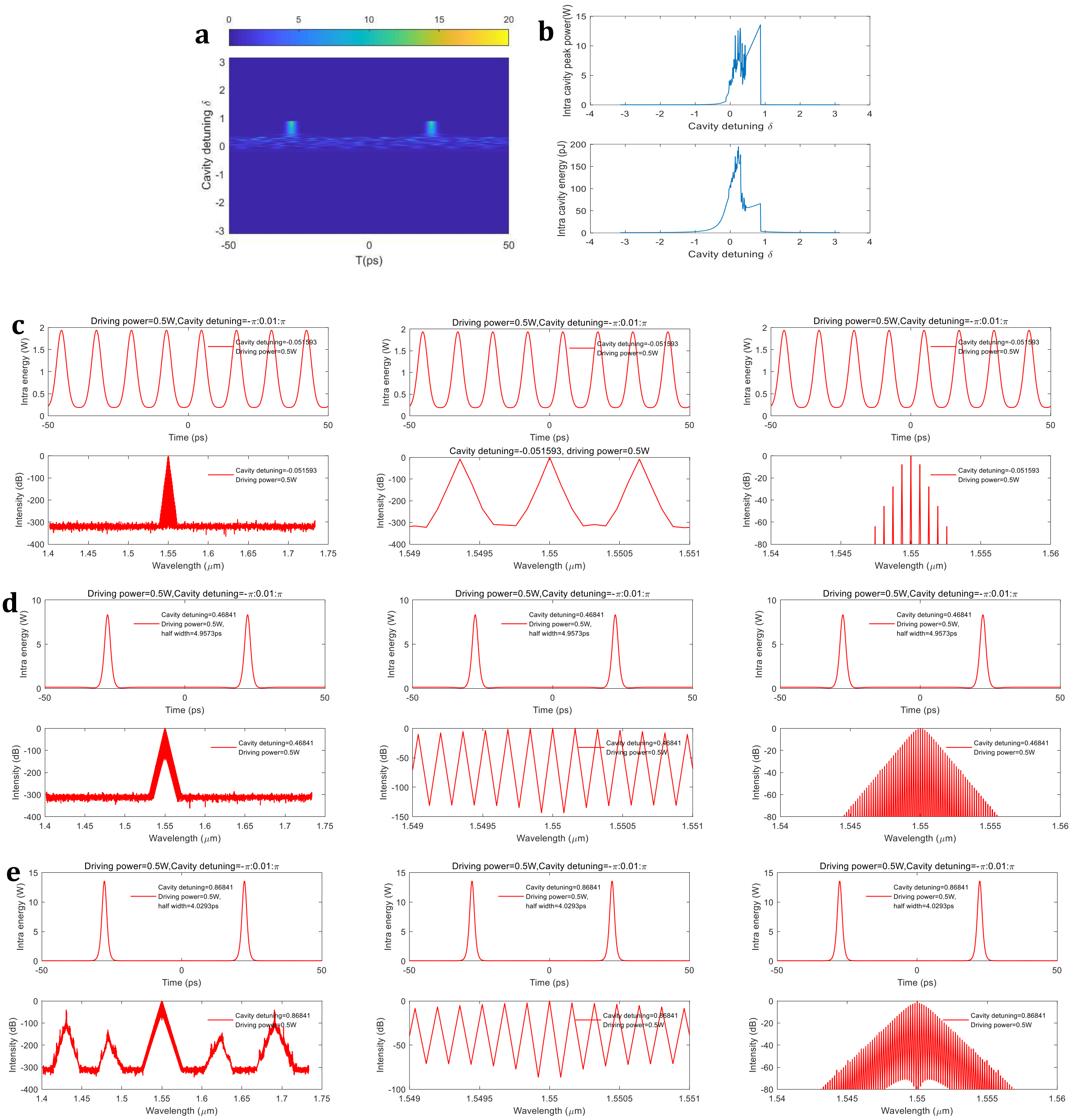

Fig. 2. Cavity optical field varying with detuning.

a Optical intensity varying with cavity detuning when driving power is 0.5W. **b** Peak power of pulse and energy in the cavity varying with detuning per roundtrip. **c,d,e** Time domain and frequency domain distribution of optical filed in the cavity when driving power is 0.45W and cavity detuning is -0.05159, 0.46841 and 0.86841, respectively.

From Fig. 2a and 2b, when cavity detuning per roundtrip varies from 0.46841 to 0.86841 with 0.5W driving power, the optical fiber cavity can produce stable solitons.
As an example, when detuning equals to -0.05159, as shown in Fig. 2c, cavity detuning per roundtrip, nonlinearity effect, dispersion effect, and loss of laser transmission can't reach a balance, so the cavity can't generate stable soliton pulses, which means the detuning value is improper.
Fig. 2d and 2e show that when detuning equals to 0.46841 and 0.86841, which are two critical values to produce stable solitons, stable solitons can be generated in the cavity with peak power from 8.38W to 13.55W and width of soliton pulses from 4.9593ps to 4.0293ps.
We should note here, from Fig. 2c, 2d and 2e, frequency combs produced by nonlinearity between laser and the optical fiber cavity are spaced evenly with a repetition frequency of FSR instead of continuous zigzag waveform shown in the figure and the zigzag waveform shows change of intensity of different frequency.

Cavity optical field varying with driving power exclusively

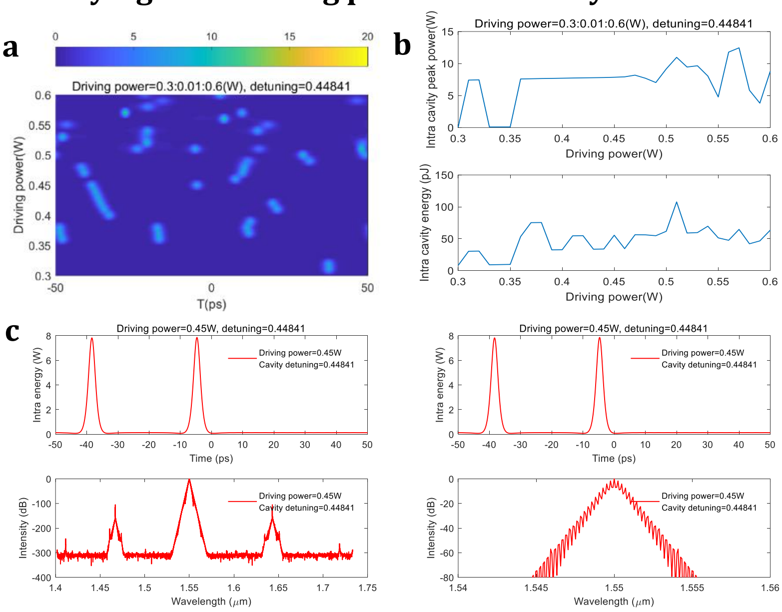

Fig. 3. Cavity optical field varying with driving power
a Optical intensity changing with driving power from 0.3W to 0.6W when detuning is 0.44841. **b** Peak power and energy of pulses varying with driving power in the cavity, respectively. **c** Time domain and frequency domain distribution of optical filed in the cavity when cavity detuning is 0.44841 and driving power is 0.45W.

From pictures above, we know that when sweeping driving power exclusively, pulse energy in the cavity varies greatly with driving power(Fig. 3b) and spectrum of pulse(Fig. 3c) shows zigzag distribution, which means that pulse in the cavity is unstable. Therefore, it inspires us that it is meaningless to adjust driving power at a fixed detuning value in the experiment.

Optical field varying with detuning and driving power simultaneously

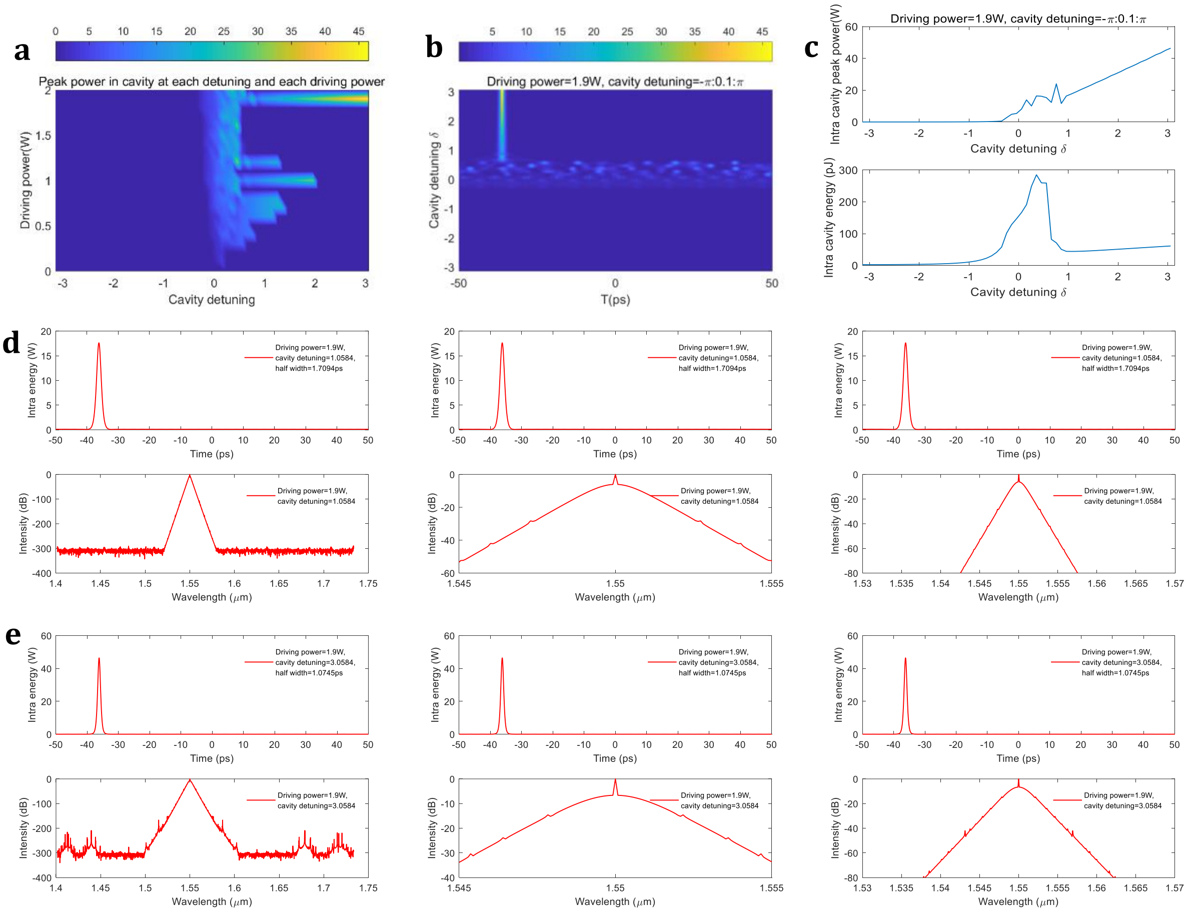

Fig. 4. Optical field varying with detuning and driving power

a Peak power in the fiber cavity at each driving power and each detuning when sweeping driving power from 0 to 2W and sweeping cavity detuning from $-\pi$ to π. **b** Optical field varying as detuning when driving power is 1.9W. **c** When driving power is 1.9W, cavity peak power and cavity energy change with cavity detuning respectively. **d, e** Time domain and frequency domain distribution of optical filed in the cavity when driving power is 1.9W and cavity detuning is 1.0584 and 3.0584 respectively.

Table1. Peak power of pulses in the cavity at each driving power

Driving power(W)	0	0.1	0.2	0.3	0.4	0.5	0.6
Peak power of pulse(W)	3.35E-54	4.179404	3.01169	8.708046	11.69198	10.71373	17.69858
Driving power(W)	0.7	0.8	0.9	1	1.1	1.2	1.3
Peak power of pulse(W)	20.73732	19.4908	20.60503	29.77361	13.86273	31.22471	17.52203
Driving Power(W)	1.4	1.5	1.6	1.7	1.8	1.9	2
Peak power of pulse(W)	20.39374	18.34124	28.45405	18.90797	19.32336	**46.41731**	26.00803

We use Matlab to sweep driving power from 0 to 2W and sweep detuning from $-\pi$ to π simultaneously, observing peak power of pulses in the optical fiber cavity varying as driving power and detuning(Fig. 4a). From table1, when driving power equals to 1.9W, peak power within the cavity reaches maximum, approximately 46W. Then we sweep detuning from $-\pi$ to π with this specific driving power and obtain pulse intensity, peak power and pulse energy in the cavity changing with detuning(Fig. 4b&4c). Fig. 4c shows the cavity can produce stable solitons when detuning value varies from 1.05847 to 3.05847. Therefore, by setting driving power at 1.9W and detuning at 1.05847 and 3.05847, soliton pulse in time domain and frequency domain is obtained. In addition, adjusting detuning from 1.05847 to 3.05847 enables width of soliton pulse to decrease from 1.7094ps to 1.0745ps and peak power to increase from 17.62W to 46.72W at the same time.

Experimental setup

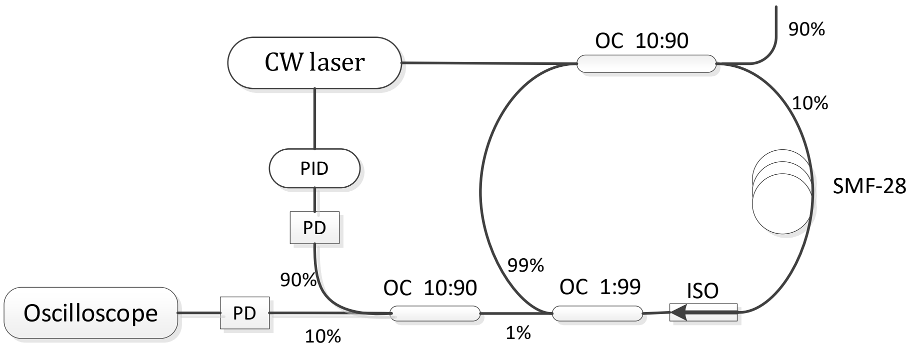

Fig. 5. Schematic of the experimental setup.

Here, continuous wave laser(CW laser), optical coupler(OC), single mode fiber-28(SMF-28), isolator(ISO),photoelectric detector(PD),proportional-integral-differential control circuit(PID).

In the experiment, considering the effects of ambient noise, ambient temperature, and frequency detuning value of the driving laser relative to resonant frequency of the cavity[2] , at first we need to lock the frequency of laser to resonant frequency of the cavity and then adjust driving power and detuning value according to simulation results to the optimal values so that cavity can produce stable soliton pulse. Also, since optical field transmission in ring cavity is sensitive to ambient temperature, it is imperative to insulate the cavity from the surroundings. Here, we build a 50-m fiber cavity and realize the lock of laser frequency to the resonant frequency of the cavity with a PID control circuit when CW laser output equals to 10mW. Besides, in order to overcome waveform drift caused by temperature disturbance, we devise a rectangular box made of pearl cotton foam board to insulate the cavity, enabling the optical pulse to display on the oscilloscope stably. A continuous wave laser of Watt magnitude and an erbium-doped fiber amplifier(EDFA) is needed here to produce enough driving power circulated in the cavity so that we can observe soliton pulses with high peak power and narrow width outputted from the cavity on the oscilloscope, according to the result of numerical simulation.

Discussion

In summary, we combine nonlinear Schrodinger equation and the periodic boundary condition between the coupled fiber and the optical fiber cavity and obtain numerical solution to them using Matlab. Also, we investigate optical pulse intensity varying with driving power and detuning value and find the optimal driving power and the corresponding detuning so that a stable soliton pulse can be produced in the cavity with the highest peak power and the minimum pulse width. With a 1.9W driving power, we can get stable solitons in the cavity with 46.72W peak power and 1.07ps pulse width. Therefore, this work lays a solid foundation for femtosecond soliton pulse generation in fiber cavity in the experiment.

Experimentally, we realize the lock of frequency between driving laser and the optical fiber cavity and insulate the cavity from surroundings with a box made of pearl cotton foam board. Consequently, we observe the stable pulse on the oscilloscope. Later work needs to be focused on improving driving power to reduce pulse width and increase peak power of soliton pulses in the cavity.

References

[1] Lugiato, L. A. and Lefever, R. Spatial Dissipative Structures in Passive Optical Systems. Phys. Rev. Lett. 58, 2209—2211(1987).

[2] Xue Dong, Qian Yang, Christopher Spiess, Victor G. Bucklew, and William H. Renninger. Stretched-Pulse Soliton Kerr Resonators. PhysRevLett.125, 033902(2020).