Spatio-Temporal Modeling of Two-Wave Ring Fibre Nonlinear Microcavity Dynamics

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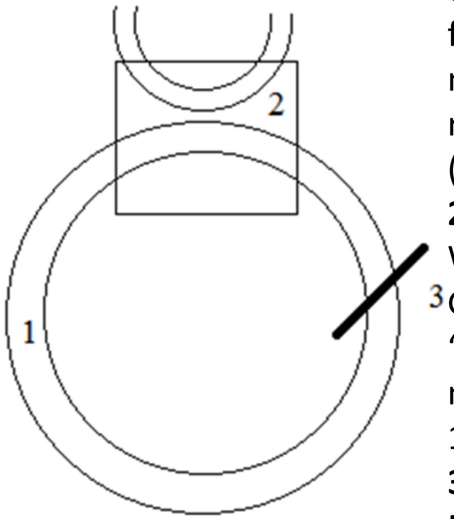
The dynamics of the nonlinear cavities and microcavities is the subject of the comprehensive investigations, both experimental and numerical, because those cavities demonstrate the effects which could be used in a broad range of various applications including super-continuum optical comb, which, in turn, lead to new methods of high-speed data transmission. Thus, it is extremely necessary to be able to predict the field behaviour inside of those microcavities. Previously used modal approach [1-3] requires solving systems of tens or hundreds of nonlinear equations, which is a time and energy consuming problem. Transport equation methods are already applied to model Raman lasers, for example, and here we apply it to model microcavities. Here we investigate the dynamics of a microcavity (1) with an intra-cavity mirror (3) installed for linear wave interface, and coupler (2) used for input and output. In this case there will be two waves in the cavity propagating in the opposite directions. There is dispersion present in the cavity, as well as the Rayleigh scattering and nonreciprocal phase shift.



References:

1. Y. K. Chembo and N. Yu, "Modal expansion approach to optical-frequency-comb generation with monolithic whispering-gallery-mode resonators," Phys. Rev. A 82, 033801 (2010).

2. T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, "Temporal solitons in optical microresonators," Nature Photonics 8, 145–152 (2014).

3. T. Herr, V. Brasch, J. D. Jost, C. Y.Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, "Supplementary information to temporal solitons in optical microresonators," Nature Photonics 8, 145–152 (2014).

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Theoretical model for waves propagation

$$2i\left(\frac{\partial F}{\partial t}+v\frac{\partial F}{\partial z}\right)+D\frac{\partial^2 F}{\partial z^2}+2\chi\left(|F|^2+2|B|^2\right)F=0,$$

$$2i\left(\frac{\partial B}{\partial t}-v\frac{\partial F}{\partial z}\right)+D\frac{\partial^2 B}{\partial z^2}+2\chi\left(2|F|^2+|B|^2\right)B=0$$

Boundary conditions:

$$F(0)=\sqrt{1-R}\sqrt{1-r}F(L)+\sqrt{R}\sqrt{A}\sqrt{1-r}+\sqrt{r}B(0),$$

$$B(L)=\sqrt{1-R}\sqrt{1-r}B(0)-\sqrt{r}(1-r)F(L)+\sqrt{Rr}\sqrt{1-R}\sqrt{A}$$

Since these are transport equations, we use an effective second order difference scheme "Cabaret" [4], what we already proved possible [5]

Equation notes

Here *F* and *B* – amplitudes of generated clockwise and counterclockwise waves respectively, *D*<0 is GVD coefficient, *v* is the group velocity, χ is the cross– and self-phase modulation coefficient, *R* is the reflection coefficient of the coupler, *r* is the reflection coefficient of the intra-cavity mirror, *A* is the intensity of the continuous wave pumping, *L* is the cavity length.

4. G. V.M. and S. A.A., “Finite difference approximation of convective transport equation with space splitting time derivative,” Matem. Mod. 10, 86–100 (1998).

5. V. Razukov and L. Melnikov, “Numerical modeling of the opposite waves spatio-temporal dynamics in a ring fibre nonlinear microcavity,” Izvestiya of Saratov University. New series. Series: Physics 20, 64–71 (2020).

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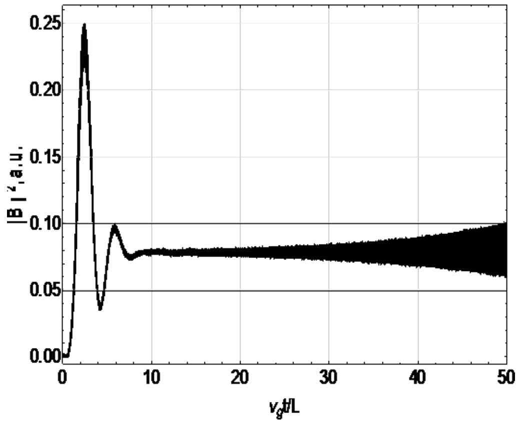
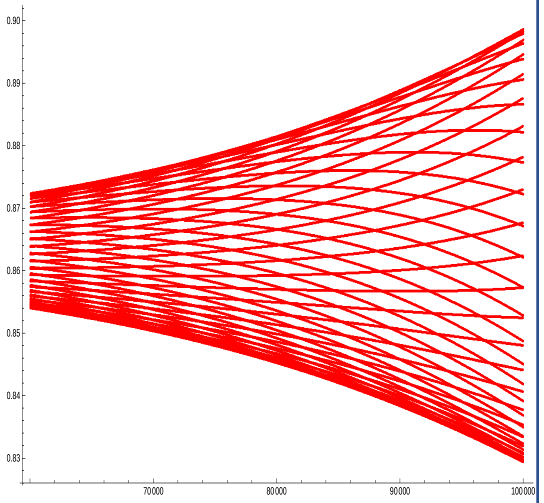
Low pumping intensity, small (r=0.005) reflection coefficient

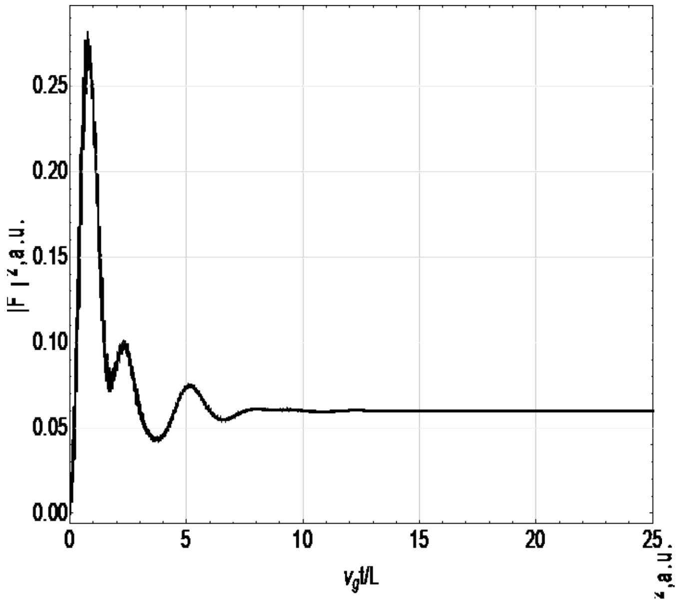


Pulse evolution during the round trips

Beat signal of the opposite running waves

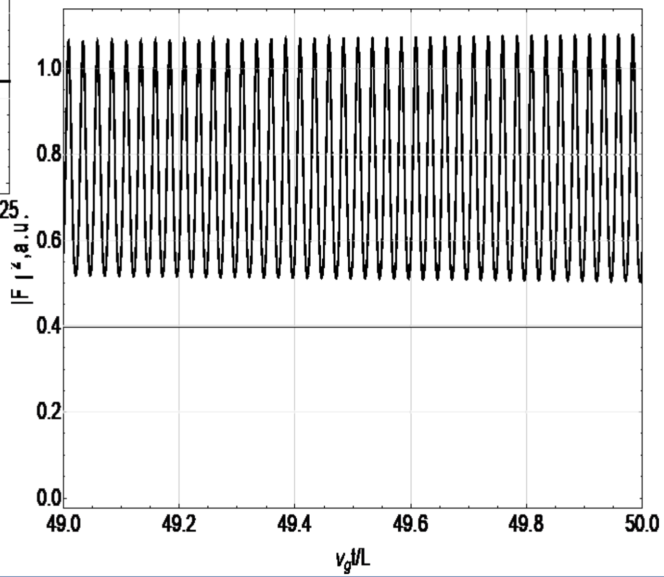


Low pumping intensity, large (r=0.05) reflection coefficient



Pulse shape

Pulse evolution during the round trips



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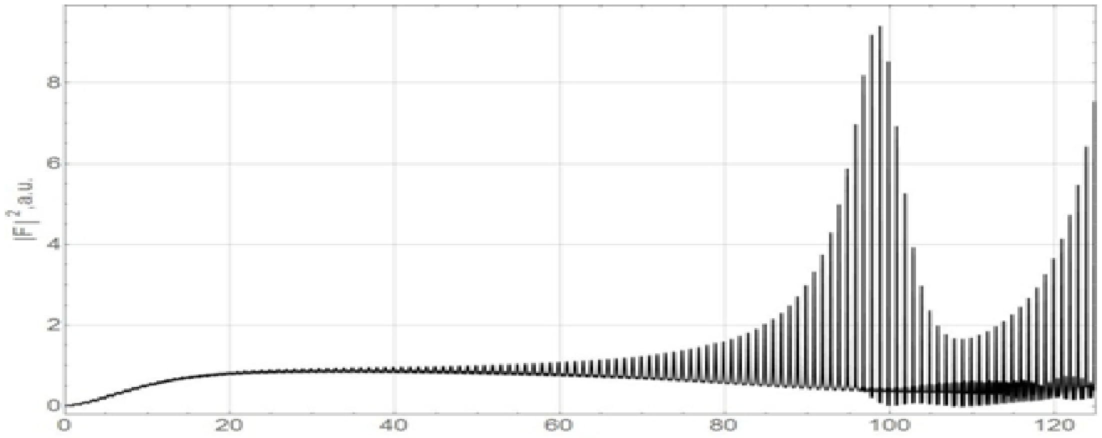
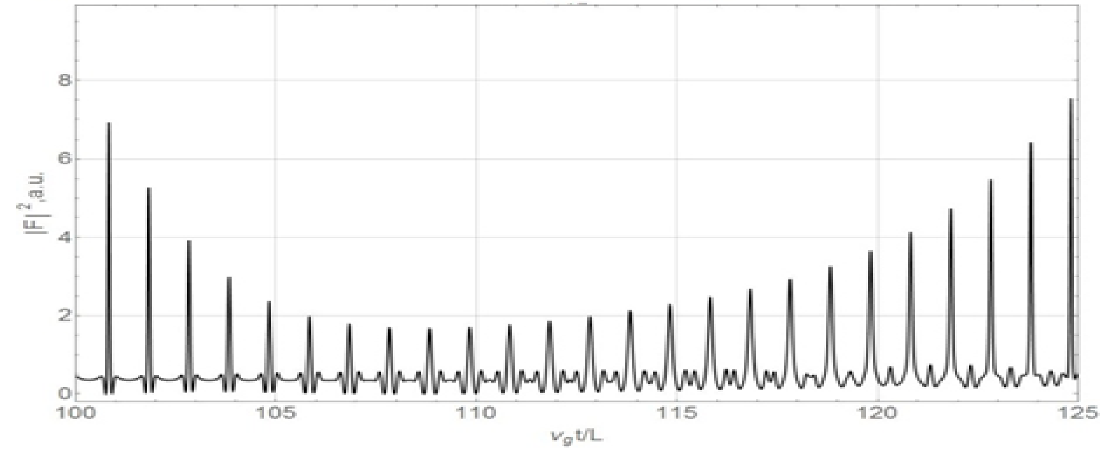
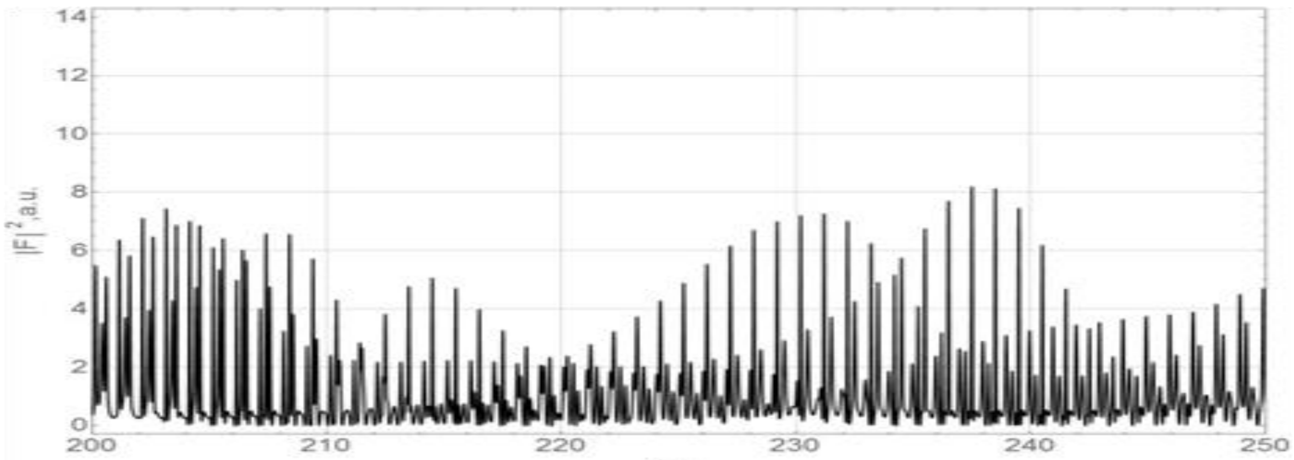
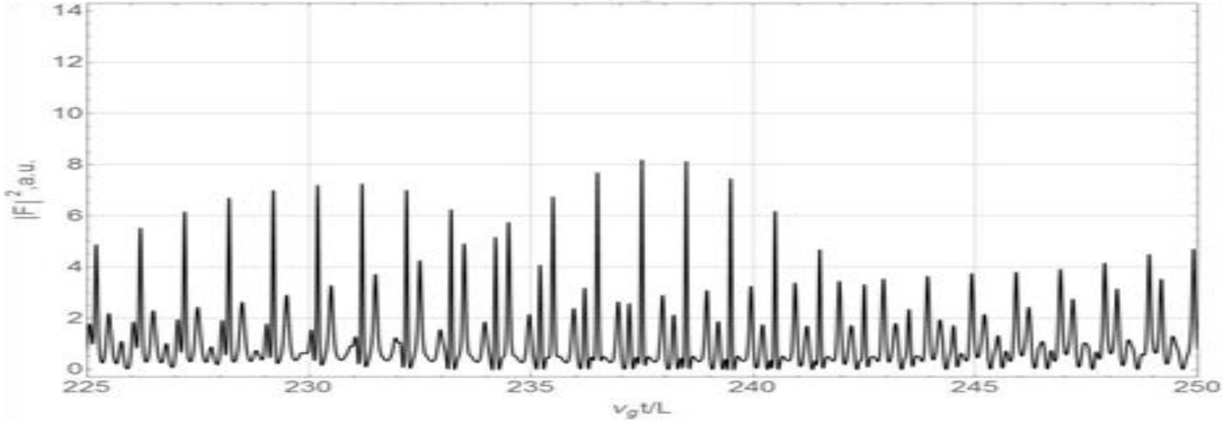
Counterporpagating wave nearly absent (χ=0.001),





Overlapping OFC forming, modulation coefficient growth to χ=0.25





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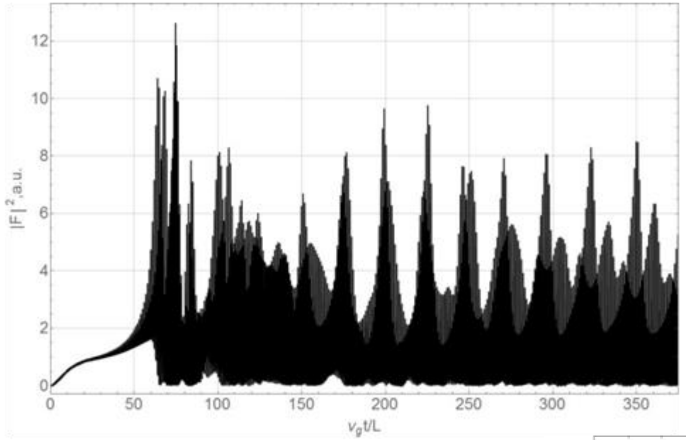
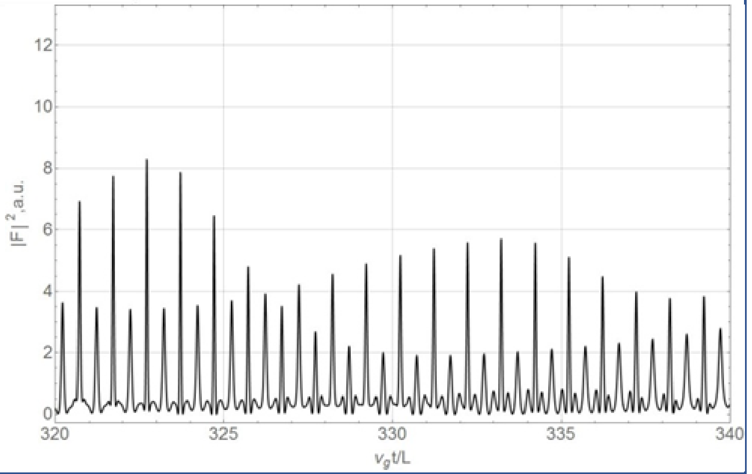
Rayleigh scattering addition to the nonreciprocal phase shift

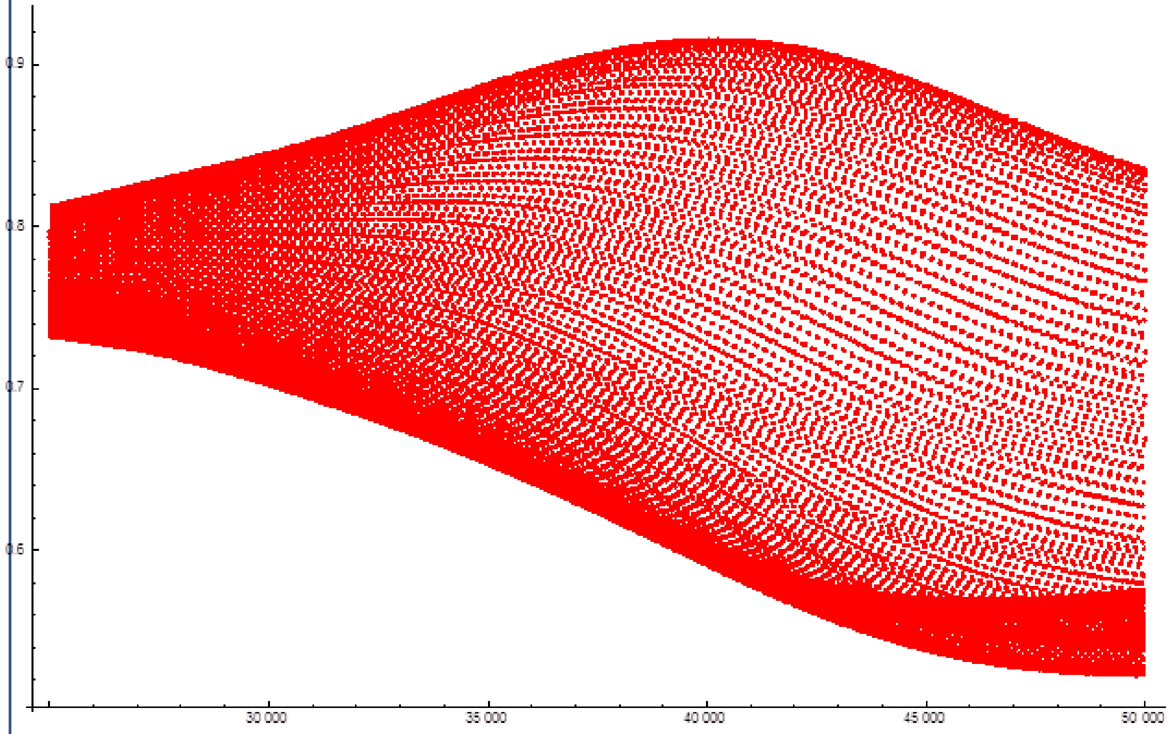


Strong background noise appeared



Less overlap in OFC's, but smaller magnitude as well

Beat Signal



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Summarizing the obtained results, we can conclude the following:

- Explicit-implicit "Cabaret“ differences method possesses increased stability
- We are capable of simulating long-term temporal dynamics in fibre microcavities with a wide number of nonlinear effects, such as GVD, phase cross and selfmodulation, Rayleigh scattering and linear waves interface
- It is easy to include Raman and SRS effects in the cavity material by using this approach, as well as most of the other nonlinear effects
- That feature is nearly impossible in modal approach, because number of equations multiplies several times with corresponding growth of the time spent solving them.

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