Comments on Self-Focusing Models of Stationary and Non-Stationary Optical Beams

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Introduction

- Self-focusing(SF) of optical beams as one of fundamental phenomena in nonlinear optics attracts a great interest of researches in quantum electronics and laser physics
- Reasons for this:
  - A strong influence of SF on interaction processes of high-power laser radiation with optical media
  - Potentials for possible applications (remote atmospheric sounding, electric discharge control, etc)
- Investigation of SF mechanisms in optical media and elucidation of adequate SF models – important directions in laser physics and nonlinear optics
- A huge number of experimental and theoretical works done in these directions during almost 50 years resulted in understanding major features of SF phenomenon, various SF models proposed and investigated theoretically and experimentally

Introduction (continued)

- However, some questions regarding these features and models (especially in ultra-short time domain) remain unclear and require further studies
- In this context I present here comments on the SF models published to date, and discuss some prospects for future studies
- Plan of the report:
  - A brief historical review of SF studies: major stage, theoretical models, experiments
  - A brief description of multi-focus structure and moving nonlinear foci models as the most adequate models of SF
  - A brief review and comments on SF of fs-pulses
  - A discussion of prospects for further studies

History of SF: major stages

- — Prediction of SF phenomenon, qualitative analysis, proposal for wave-guiding model (Askaryan, 1962)
- — First observations of SF (Hercher, 1964; Pilipetski and Rustamov, 1965)
- — First comprehensive theoretical studies of SF, proposal for self-trapping model (Chiao, Garmire and Townes; Talanov, 1964)
- — Further theoretical studies:
  - Determination of main characteristics of SF: critical power, SF length, self- phase modulation, spatial instability (Bespalov, Talanov, Akhmanov, Khokhlov, Sukhorukov, Kelly, Marburger, 1964-1972)
  - Proposal for alternative SF models: multi-focus structure and (Dishko, Lugovoi, and Prokhorov, 1967), moving nonlinear foci (Lugovoi and Prokhorov, 1969)
- — Purposeful experimental studies of SF confirming adequacy of MFS-MNLF models (Loy and Shen, 1969; Korobin, et al, 1970; Manenkov, et al, 1970)

History of SF (continued)

—**A new stage in SF studies, fs-pulses:**

- **First observation of SF of fs-pulses (filamentation) in air (Mourou, et al, 1995)**
- **Subsequent studies:**
  - —**Elucidation of main characteristics of filamentation: length, diameter, and energy of filaments, transformation of spectrum-supercontinuum and conical emission (Mysyrowicz, et al, 1996; Chin, at al, 1997)**
  - —**Theoretical studies, proposals for filamentation models: self-guiding, self-trapping, moving foci and refocusing, spatial replenishment (Braun, et al; Mysyrowicz, et al; Kandidov, et al; Molony, et al, 1997)**
  - —**Continuing studies of fs-pulses filamentation in air, other gases, and condensed media (many researchers in many countries, 1997- up to now)**

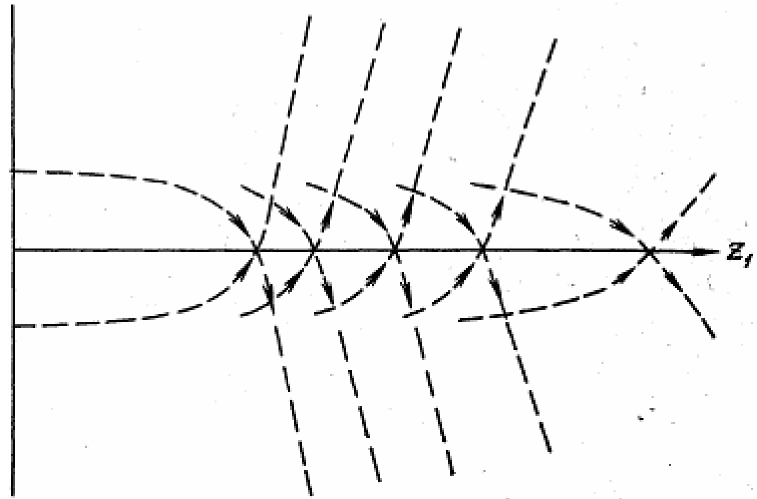
MFS-MNLF models

- Analysis of SF studies shows: main results can be explained most adequately on a basis of MFS-MNLF models
- Below I describe briefly a theory of these models and some experimental results confirming their adequacy
- MFS model has been formulated (Dyshko, Lugovoi, and Prokhorov, 1967) on a base of numerical investigation of a light beam propagation in Kerr-type nonlinear medium described by nonlinear wave equation:

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r}\frac{\partial E}{\partial r} + 2ik\frac{\partial E}{\partial z} + n_2 k^2 |E|^2 E = 0 \qquad (1)$$

- Established: a series of nonlinear foci is formed on a beam propagation axis, Z:

Fig.1



MFS-MNLF models (continued 1)

- **Location of nonlinear foci:**

$$\xi_{\Phi m} = \frac{\chi_m}{N_m} \frac{k\bar{a}_0^2}{\sqrt{P_0 / P_{cr}^{(m)}} - 1} \quad (2)$$

P_0 and a_0 - incident beam power and radius,respectively, $P_{cr}^{(m)}$ is critical power for m-th focus $P_{cr}^{(m)} \cong mP_{cr}^{(1)}$, $P_{cr}^{(1)} = cn_0 N_1^2 / 8n_2k^2$,

—For a stationary light beam (time independent power $P=P_0$) the location of nonlinear foci is fixed on Z-axis whereas for a non-stationary beam (P=P(t)) foci move along Z-axis

—Fig.2 illustrates formation of moving multi-focus structure in a fast-response Kerr-medium. Here solid curves - location of nonlinear foci at various pulse power, dashed curves- light pulse shape

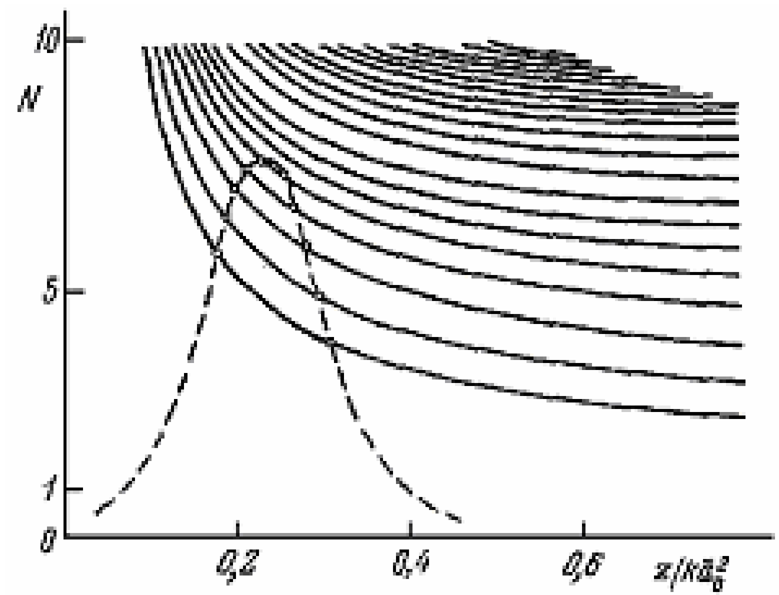


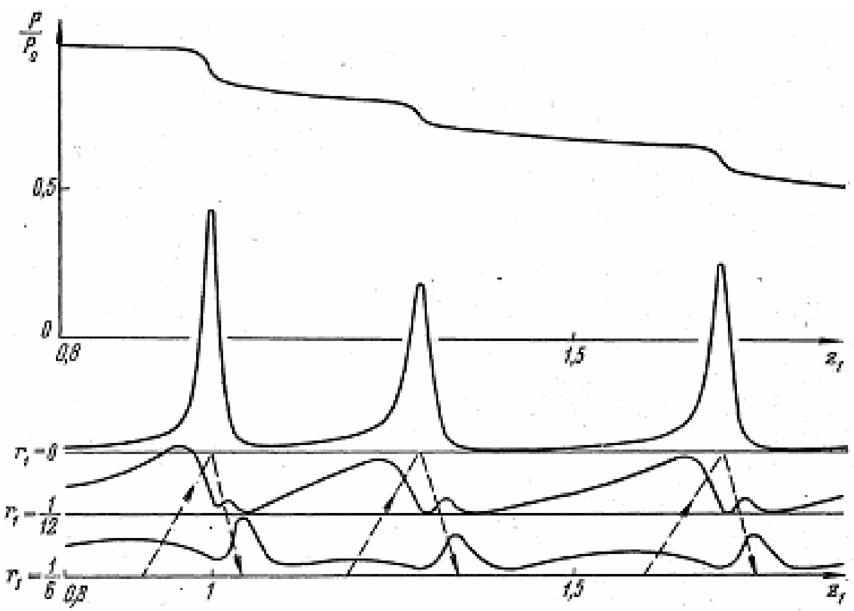
Fig. 2

MFS-MNLF models (continued 2)

— Theoretically established:

- Only a portion of an initial beam power, $\cong P_{cr}^{(1)}$, flows through each nonlinear foci, a rest power of the beam is absorbed and diffracts in the foci at rather large angles
- Longitudinal and transverse sizes of the foci, as well as their location on Z-axis, depend on physical processes in the media (nonlinear absorption, ionization, etc)
- However, multi-focus structure is, in general, remained, i.e. is stable to perturbations of nonlinear properties of the media(Fig. 3 illustrates this fact for a medium with 3-photon absorption)

Fig.3



MFS-MNLF models (continued 3)

- MFS model is stable also to variation to spatial beam profile (super-Gaussian beams were theoretically investigated, Danileiko, et al, 1981)
- Multiple filamentation, observed in case of inhomogeneous beams, is naturally explained in a frame of MFS-MNLF models: separate MFS are formed if intensity spikes of the beam exceed P_{cr}.

MFS-MNLF models: experiment

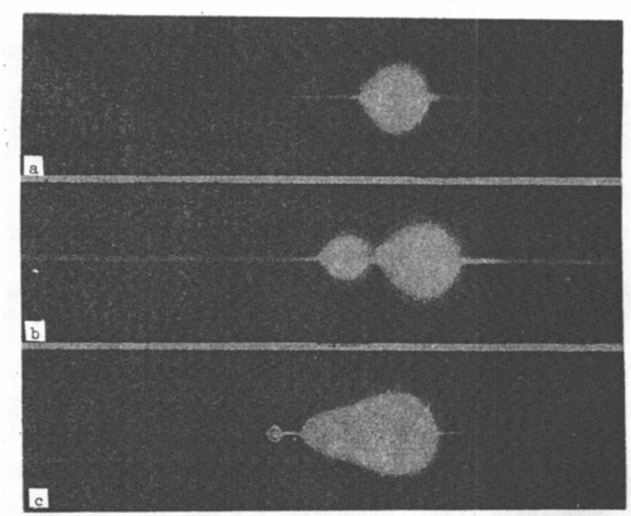
- At earlier stages of SF studies (1962-1970) observed filaments were interpreted in a frame of self-waveguide-self-trapping concept
- In 1969-1970 purposeful experimental studies have been performed to prove what models,self- waveguide or moving nonlinear foci, are adequate:
  - Observation of spatial-temporal evolution of a laser beam at the exit and inside of a nonlinear optical liquid cell (Loy and Shen, 1969)
  - Observation of spatial-temporal evolution of the laser beam in a nonlinear optical liquid cell applying high-speed temporal resolution technique (Korobkin, et al, 1970)
  - Observation of spatial structure of a laser beam in a nonlinear medium (glass) at variation of temporal laser pulse shape (Lipatov, Manenkov, and Prokhorov, 1970)

MFS-MNLF models: experiment (continued 1)

- All these experiments have confirmed adequacy of the moving nonlinear foci model
- Here we present the results of our experiment (Lipatov, Manenkov, Prokhorov, 1970) in which self-focusing of ruby laser beam in glass has been investigated at different temporal pulse shapes: bell-like, triangular, and rectangular (flat-top)
  - In cases of bell-like and triangular pulse shapes filamentary damage in the glass has been observed, whereas in the case of rectangular pulse shape the point-like damage has been observed.
  - Fig.4 illustrates the latter case:

  laser-induced light sctterring patterns at various incident powers:
  (a)P_i=P_d , (b) P_i=3P_d ,(c) P_i=6P_d

Fig. 4



MFS-MNLF models: experiment (continued 2)

- Interpretation of the results:
  - **Filamentary damage is caused by non-stationary SF (moving nonlinear foci)**
  - **Point-like damage is the result of stationary SF (standing nonlinear foci)**

SF of fs-pulses

- A huge number of experimental and theoretical works has been carried out on SF of fs-pulses during last 15 years
- Main results of experimental works:

  In air:

  - **Strongly pronounced beam filamentation is observed at $P_o \geq P_{cr}$ (≈3GW) : very long($l_f \geq 10$ m)and thin ($d_f \cong 100$ μm) laser light and plasma filaments**
  - **Light energy in the filament $E_f \cong 6\% P_0$**
  - **Multiple filaments are observed at $P_o \geq 10P_{cr}$**

  - **A strong transformation of spectrum** is **observed** at $P_o > P_{cr}$:
    - large broadening: **super-continuum (230 nm-4 μm)**
    - **Specific conical emission**

  In condensed media:

  - P_{cr} is an order of magnitude less than in gases,
  - $l_f \cong$ several cm,
  - $d_f \cong 2$ μm

SF of fs-pulses(continued 1)

- **Theoretical results** :
- **Theoretical studies of fs-pulse filamentation (especially in air) have been performed by several groups in Russia, US, France, Canada, and other countries**
- **All these studies were based (with some variations) on numerical solutions of nonlinear wave equation (nonlinear Schrodinger equation) taking into account ordinary light diffraction and several nonlinear effects: Kerr-nonlinearity of medium refractive index, multi-photon absorption (MPA), and plasma generation due to MPA**

$$2i\frac{\partial E}{\partial z} + \frac{1}{k_0}\Delta_\perp E - k''\frac{\partial^2 E}{\partial t^2} + k_0 n_2\left(|E|^2 + \tau_K^{-1}\int_{-\infty}^{1} e^{-(t-t')/\tau_K}|E(t')|^2 dt'\right)E$$

$$-k_0\frac{\omega_{pe}^2(\rho)}{\omega_0^2}E + i\beta^{(K)}|E|^{2K-2}E = 0 \qquad (3)$$

$$\frac{\partial \rho}{\partial \tau} = \frac{\beta^{(K)}}{K\hbar\omega_0}|E|^{2K}\left(1 - \frac{\rho}{\rho_{at}}\right) \qquad (4)$$

SF of fs-pulses (continued 2)

- **Computer simulation results have been interpreted on a base of different models:**
  - **Self-channeling (Braun, et al, 1997)**
  - **Dynamic spatial replenishment (Molonely, et al, 1997)**
  - **Moving foci and refocusing (Kandidov, et al, 1997)**
  - **Slice-by-slice self-focusing (Chin, et al, 1997)**
- **An analysis (Lugovoi and Manenkov, 2005) of these computer simulations has shown:**
  - **some shortcomings: incomplete description of group velocity dispersion- not taking into account a plasma component, inadequate interpretation of delayed response term in Kerr -nonlinearity of refractive index**
  - **SF models suggested coincide(in essence) with Lugovoi-Prokhorov MFS-MNLF models although terminology used is different**

SF of fs-pulses (continued 3)

- **Indeed,for example:**
  - **"self-guided light strings" (Moloney, et al), in fact, correspond to "moving nonlinear foci" in Lugovoi-Prokhorov model**
  - **"nonlinear robust mode" correspond to a portion of the beam flowing through the nonlinear focus in Lugovoi-Prokhorov model**
  - **"dynamic spatial replenishment" corresponds to the process of multi-focus structure formation in Lugovoi-Prokhorov model**
  - **Similarly, "slice-by-slice self-focusing"(Chin, et al) corresponds to multi-foci structure formation in Lugovoi-Prokhorov model**

SF of fs-pulses(continued 4)

- **Therefore, available experimental and theoretical results on SF of fs-pulses are in a qualitative agreement with Lugovoi-Prokhorov MFS-MNLF models**
- **At the same time, taking into account a complexity of processes involved into SF of fs-pulses (strong influence of plasma formation, etc), further studies, both experimental and theoretical, are required using new approaches**

SF of fs-pulses: prospects

- **Use of laser pulses with variable temporal shapes (similarly to that used in studies of SF of ns-pulses) seems to be promising approach to study and control SF processes**
- **Indeed,an analysis (Manenkov, 2008) has shown:**

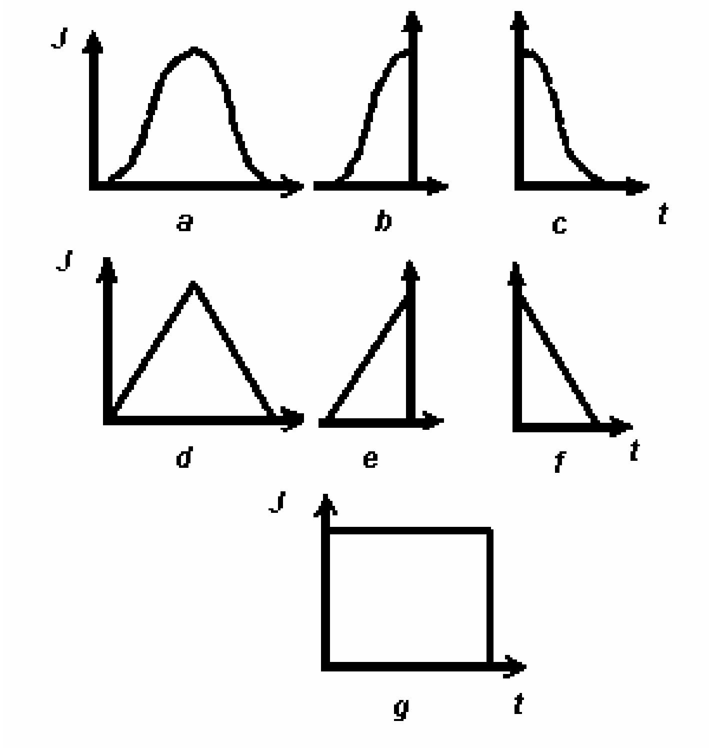


Fig. 5

– **If bell-like(e.g. Gaussian) or triangular pulse shapes are used (symmetric -Fig. 5a,d and asymmetric -Fig. 5b,c,e,f) different filamentary spatial structures of the beam intensity should be observed because of different effects of laser-induced plasma on rise and fall times of the pulse propagating in a medium**

SF of fs-pulses: prospects (continued 1)

- **All bell-like and triangular pulse shapes correspond to non-stationary SF**
- **Quite different beam structures should be observed if rectangular (flat-top) laser pulse shape is used: a spatially standing discrete nonlinear foci structure (no filamentation!) corresponding stationary SF**
- **Spectral properties of optical radiation propagating in nonlinear media have to be also significantly different at various pulse shapes because of different character of spectral broadening due to self-phase modulation:**

$$\Delta\omega = -\frac{d\varphi_{nl}}{dt} = -\frac{d}{dt}\left(\frac{\omega}{c} n_2 I(t)\cdot L\right) \qquad (5)$$

φ_{nl} – nonlinear phase
ω- central frequency of laser radiation
n_{nl} – nonlinear refractive index
$I(t)$ – intensity
L – interaction length

SF of fs-pulses: prospects (continued 2)

- **In cases of bell-like and triangular pulses different spectral broadening should be observed depending on *I*(*t*) shape**
- **In particular, if asymmetric pulse shapes are used blue-shifted or red-shifted spectral broadening should be observed**
- **In case of rectangular pulse spectral broadening due to self-phase modulation should be absent ($d\varphi_{nl}/dt=0$)**

Conclusions

- **SF phenomenon of optical beams has been studied to date rather well , especially in ns-ps pulse duration domain**
- **Main features of the phenomenon observed in ns-ps range are explained most adequately on the basis of Lugovoi-Prokhorov MFS-MNLF model**
- **This model can, we believe, also explain features of SF in shorter (fs) pulse duration range**
- **However, for more complete understanding of SF in fs-range further experimental and theoretical studies are required**
- **To our view, a perspective approach for such studies is to use laser pulses with variable temporal shapes**