Photonic droplets in a medium of carbon nanotubes

Ilya S. Dvuzhilov, Yulia V. Dvuzhilova, Alice M. Belonenko, Evgeniya V. Boroznina and Mikhail B. Belonenko*

Volgograd State University, 400062 Volgograd, Russia

Abstract. The numerical research of the photonic droplets dynamic in a carbon nanotube medium has been carried out. A stable propagation of these pulses has been detected at times down to tens of picoseconds. The propagation features of pulses at various parameters (velocity and pulse amplitude) have been shown as well.

Photonic droplets are currently an object of great interest to non-linear optic researchers, due to their unusual dynamic of propagation and their properties [1]. Photonic droplets are interconnected, limited states of light that are resistant to size and shape changes, due to the balance of competing, attractive and repulsive forces. These forces arise by way of electromagnetic fields of a non-linear, non-local optical medium.

The definition of a photon droplet was introduced by a scientific group led by Manuel Valiente in January 2018. Photonic droplets are highly connected to solitons by their nature. But photonic droplets may not preserve their shape during the interaction with a medium when they propagate (in an excited state), unlike solitons [2]. In this paper, we show that photon droplets should occur as a result of competition between non-linear terms that describe scattering in s- and d- waves, due to which a symmetric ground state with zero orbital momentum is formed.

Another physical object with unique properties in non-linear optics is carbon nanotubes (CNTs). CNTs are desirable in non-linear optics. They contribute to the development of research in the field of optical pulse propagation and the subsequent development of optical devices based on these, but the main and the most important quality possessed by carbon nanotubes is the possibility to use them as a medium for photonic droplet formation [3].

The typical relaxation time for electrons inside CNTs can be estimated as 3×10^{-13} s, so an electrons ensemble at times typical for problems of a few cycle pulses dynamic (order 10^{-14} s) can be described by using the Boltzmann collisionless kinetic equation [4]:

$$\frac{\partial f}{\partial t} - \frac{q}{c} \frac{\partial A_z}{\partial t} \frac{\partial f}{\partial p} = 0 \quad (1)$$

where $f = f(p_z, s, t)$ - is distribution function, implicitly depending on coordinates (due to the dependence of the vector potential A on the coordinate), herewith the distribution

* Corresponding author: dvuzhilov.ilya@volsu.ru

function f at the initial moment of time coincides with the equilibrium distribution function of Fermi F_0 :

$$F_0 = \frac{1}{1 + \exp\{E(\mathbf{p})/k_b T\}}$$

where T – is the temperature, k_b – is the Boltzmann constant.

The current density $\mathbf{j} = (0, 0, j_z)$:

$$j_z = \frac{q}{\pi\hbar} \sum_s \int dp_z v_z f$$

where $v_z = \partial E(\mathbf{p})/\partial p_z$ is the group velocity of electrons. Solving this equation by using the methods of characteristics, we arrive at:

$$j_z = \frac{q}{\pi\hbar} \sum_s \int_{-q_0}^{q_0} dp_z v_z \left[p - \frac{q}{c} A_z(t) \right] F_0(\mathbf{p})$$

As a result of this paper we have found that photonic droplets in the medium of CNTs propagate stably, at times of the order of 10 ps. The dependencies of the dynamics of photon droplets with different velocities in a CNT medium have been discovered. It has been shown that the energy of photonic droplets remains limited in a space when the velocity of photonic droplets changes, but a slight change in droplet shape also takes place. We have also shown that an increase in the amplitude of a photon droplet during propagation from a CNT in a medium affects the formation of a more complex transverse structure at the trailing edge of the pulse.

The reported study was funded by RFBR and the government of Volgograd region according to the research project № 19-42-343002, № 19-43-340005.

References

1. G. Fibich, B. Ilan, Opt. Lett., **29**, 8 (2004).
2. Niclas Westerberg, Kali E. Wilson, Callum W. Duncan et al, Phys. Rev. A., **98**, (2018).
3. A.V. Zhukov, R. Bouffanais, M.B. Belonenko, I.S. Dvuzhilov, Yu.V. Nevzorova, Appl. Phys. B., **123**, 196 (2017).
4. S.J. Tans, M.H. Devoret, H. Dai et al, Nature, **386**, (1997).