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# Nonstationary photonic jet from dielectric microsphere

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ABSTRACT

A photonic jet commonly denotes the specific spatially localized region in the near-field forward scattering of a light wave at a dielectric micron-sized particle. We present the calculations of the transient response of an airborne silica microsphere illuminated by a femtosecond laser pulse. The spatial area constituting the photonic jet is theoretically investigated and the temporal dynamics of jet dimensions as well as of jet peak intensity is analyzed. The role of morphology-dependent resonances in jet formation is highlighted. The evolution scenario of a nonstationary photonic jet generally consists of the non-resonant and resonant temporal phases. In every phase, the photonic jet can change its spatial form and intensity.



## 1. Introduction

A “photonic jet” (PJ) commonly is associated with a narrow high-intensity optical flux formed in the proximity of the shadow surface of transparent dielectric symmetric bodies (spheres, cylinders, spheroids) with a diameter comparable to or somewhat larger than the wavelength of the incident optical radiation. The physical origin of PJ formation arises from the interference of the diffracted and refracted light waves incident onto a particle. A most striking and specific feature of PJ is the extremely high spatial localization of the light field in the transverse direction (relative to the direction of incidence), which in contrast to the conventional high numerical aperture focusing optics, can lead to sub-wavelength dimensions of the photonic jet. Thus, the PJ from micron-sized particle bears to the highest extent the diffractive features of wave-particle interaction process.

The investigations of PJ from symmetric particles were started from the theoretical work of Chen et al. [1] where the authors for the first time noted that a jet-like light structure, which was formed in the geometric shadow of a transparent silica microcylinder exposed to a light wave experienced extremely high sensitivity to minor refractive index inhomogeneity (small inclusions, nanoparticles, etc.) of the surrounding medium [2]. This specific field structure, called a *photonic jet* (or *photonic nano*jet [1]), is characterized by a sub-diffraction transverse dimension (smaller than a half-wavelength) and can extend conserving its shape to the distances of several wavelengths. This fact attracts a particular interest to the PJ phenomenon and benefits in wide practical applications, e.g., in designing the ultrahigh-resolution (nanometer-scale) optical sensors [3]. Besides, the PJ is used as surgical optical scalpel [4], optical tool for nano-object manipulation [5], element in optical data storage with ultrahigh resolution [6], and in the technology of nano-photolithography [7]. A rather thorough review of works devoted to theoretical and experimental investigations of the PJ phenomenon can be found in the recent paper [8].

As a rule, the classical scenario of PJ formation corresponds to the exposure of a dielectric microsphere to a continuous-wave radiation. This involves the use in numerical simulation the stationary Lorenz–Mie theory. At the same time, both optical technologies and biomedicine demonstrate recently the growing practical interest to laser systems generating ultra-short laser pulses. This type of laser radiation is attractive because it

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becomes possible to obtain extremely high peak intensity with low pulse energy. As a striking example, we can mention Ref. [9], where the authors have experimentally demonstrated the laser-induced perforation of living cell membranes using the photonic jet generated by micron-sized polystyrene spheres exposed to a femtosecond pulse of Ti:sapphire laser. It was noted that the proposed technology of femtosecond optical perforation, in contrast to the traditional technology using gold nanoparticles, did not lead to the death of a living cell.

At the same time, when the laser radiation is short the characteristic times of optical field formation inside and outside a scatterer can be comparable to the incident pulse duration. Thus, the transient scattering dynamics should be taken into account in the simulations. In previous works [10–13] based on internal optical field calculations was shown that the nonstationarity of light scattering at a transparent spherical particle manifests itself in temporal distortion of diffracted radiation and, in particular, in its temporal retarding. In the spectral domain, the scattering of an ultra-short and hence broadband optical signal on a dielectric particle may acquire the resonance character. The high-quality electromagnetic eigenmodes of a dielectric sphere, called *whispering-gallery modes* (WGM), are excited in the internal optical field of a particle. As compared to the laser pulse duration, these modes have long lifetimes and they delay the incident radiation inside the particle [13] thus introducing the mentioned features into the light scattering.

In this paper, we theoretically investigate the temporal dynamics of the near-field scattering of ultra-short laser radiation at a transparent dielectric spherical microparticle, which results in the formation of nonstationary photonic jet. The numerical simulations based on the nonstationary Mie scattering theory are used to study the temporal evolution of the spatial shape and main characteristics of photonic jet.

## 2. Theoretical model of nonstationary scattering of a laser pulse by a spherical particle

Before considering the theoretical model and discussing the results of simulations, some remarks should be given. Below we will consider the linear scattering of a laser pulse at a micron-sized silica microsphere, which imposes certain constraints on the energy parameters of the incident radiation to avoid manifestation of optical nonlinearity of the particulate material. The strongest nonlinear optical effects in a solid dielectric such as silica are Kerr self-focusing and optical breakdown. In the near-IR wavelength region, the energy threshold of silica destruction by optical radiation is about 0.1–0.3 μJ, whereas the Kerr self-focusing power is at a level of ~2 MW [14]. Since analogous data for the visible region are unavailable in the literature, we will take these values as a basis for approximate estimation of nonlinear effect thresholds.

Then, for the present situation of irradiation of a particle with radius $a_0=2$ μm by a laser pulse with carrier wavelength $\lambda_0=0.4$ μm and temporal duration $t_p=10$ fs we immediately obtain that the peak intensity should not exceed $I_0 \sim 10^{13}$ W/cm$^2$. Besides, if we take into account the focusing effect of optical radiation by the particle, this value should be additionally decreased. In the considered situation, this decrease should be by approximately three orders of magnitude (see, Fig. 2c below). Thus, the condition of the absence of nonlinear effects in a silica particle during the laser pulse reads as $I_0 < 10^{10}$ W/cm$^2$.

In addition to the effect of optical nonlinearity upon ultra-short radiation scattering it is also important to take into account the chromatic dispersion of particle material, which manifests itself in the dependence of the linear refractive index $n$ on the laser wavelength $\lambda$. This leads to the changes in optical lens power of a particle proportional to the product $n(\lambda)a_0$ and to the spectral transformation (broadening/narrowing) of the pulse due to the group velocity dispersion during the propagation through the particle, which can be described by the coefficient $k''_\omega = \partial^2 k/\partial\omega^2\big|_{\omega_0}$ ($\omega$ is laser circular frequency, and $k=2\pi n/\lambda$ is the wave number in medium).

The chromatic dispersion of a material is usually described by the Sellmeier dispersion relation, and for fused silica it looks as follows [15]:

$$n^2(\lambda) = 1 + \sum_{m=1}^{3} A_m \frac{\lambda^2}{\lambda^2 - \lambda_m^2} \tag{1}$$

where $A_1=0.6962$, $A_2=0.4079$, $A_3=0.8975$, and $\lambda_1=0.0684$ μm, $\lambda_2=0.1162$ μm, $\lambda_3=9.8962$ μm. The laser pulse with the duration $t_p$ and carrier wavelength $\lambda_0$ has the spectrally limited half-width $\Delta\lambda=\lambda_0^2/ct_p$, i.e., at $t_p=10$ fs and $\lambda_0=0.4$ μm we obtain $\Delta\lambda \approx 0.053$ μm. In the wavelength range $\lambda_0 \pm \Delta\lambda$, Eq. (1) gives the corresponding variation of silica refractive index $n$ from 1.4656 to 1.4769 that can be neglected. In this situation, the second-order group velocity dispersion coefficient is $k''_\omega=10^3$ fs$^2$/cm and consequently the silica dispersion in the 0.4-μm range is normal and leads to the twofold broadening of the pulse spectrum at the characteristic path length $L_D = t_p^2/k''_\omega \sim 1$ mm, which exceeds the particle radius many times. Thus, in the following calculations we will ignore dispersion properties of silica particle.

Additionally, because of silica transmission window ranging approximately from 0.2 μm to 2.8 μm [16] we will completely neglect silica light absorption. The question on how the PJ parameters depend on material absorption is discussed in [17].

To study the temporal evolution of optical pulse scattering at a particle, we use the nonstationary Mie theory (NMT) developed in Ref. [10] and extended to the case of shaped beams in Ref. [18]. Actually, the NMT is a combination of the Fourier spectral analysis and the stationary Lorenz–Mie theory [19,20]. In the framework of NMT, the initial nonstationary problem of the diffraction of a broadband radiation at a dielectric sphere reduces to the problem on the stationary light scattering of a set of monochromatic Fourier harmonics. The scattering properties of the particle are characterized by the *spectral response function* $\mathbf{E}_\delta(\mathbf{r};\omega)$ being the traditional Mie series taken for all frequencies $\omega$ from initial pulse spectrum at every space point $\mathbf{r}$. The detailed description of this technique and some examples of its numerical