Extension of filament propagation in water with Bessel-Gaussian beams
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Citation: AIP Advances 6, 035001 (2016); doi: 10.1063/1.4943397
View online: http://dx.doi.org/10.1063/1.4943397
View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/6/3?ver=pdftov
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Construction of a subpicosecond double-beam laser photolysis system utilizing a femtosecond Ti:sapphire oscillator and three Ti:sapphire amplifiers (a regenerative amplifier and two double passed linear amplifiers), and measurements of the transient absorption spectra by a pump-probe method
We experimentally studied intense femtosecond pulse filamentation and propagation in water for Bessel-Gaussian beams with different numbers of radial modal lobes. The transverse modes of the incident Bessel-Gaussian beam were created from a Gaussian beam of a Ti:sapphire laser system by using computer generated hologram techniques. We found that filament propagation length increased with increasing number of lobes under the conditions of the same peak intensity, pulse duration, and the size of the central peak of the incident beam, suggesting that the radial modal lobes may serve as an energy reservoir for the filaments formed by the central intensity peak.

I. INTRODUCTION

Filamentation by femtosecond laser radiation, propagating in nonlinear media, facilitates a number of applications, including remote sensing, attosecond physics, and lightning control. In such settings, extended filaments are desirable, and various techniques aiming to prolong their length have been explored. The substantial extension of optical filaments continues to attract considerable interest and much still remains to be understood. Commonly, filamentation is considered to be a result of a dynamic balance of the Kerr self-focusing of an intense beam and the defocusing involving the self-generated weak plasma and the effect of free electrons. It is of interest to investigate how different incident laser transverse modes affect filament propagation dynamics.

The linear propagation of Bessel beams that exhibits a suppressed diffraction during propagation attracted considerable attention. The studies of nonlinear Bessel beams has also revealed a possibility for the existence of localized and stationary solutions. A possible scenario where filaments appear because of spontaneous beam reshaping into a conical wave was investigated by suggesting an interpretation of femtosecond pulse filamentation not related to the effect of self-generated weak plasma. The survival of filaments transmitted through clouds was explained by a dynamic energy balance between the formed quasi-solitonic structure and the surrounding laser photon bath, which acts as an energy reservoir. The self-reconstruction properties of filaments and their extension were also explained in terms of the energy reservoir surrounding filaments. Nonlinear dynamics of pulsed Bessel beams and possible applications were also investigated.

Ideal Bessel beams are known to be diffraction-free when they propagate in vacuum. Although these beams do not exist, the use of approximate or quasi-Bessel beams has long been suggested in diverse areas of optical physics, since such beams maintain long propagation lengths in optical media by virtue of the strongly suppressed diffraction of their central lobe. When a Bessel beam is compared to a Gaussian beam with the same diameter of the central peak, it shows...

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a remarkable resistance to diffraction in the linear propagation regime.\textsuperscript{25} Recent theoretical studies on filamentation dynamics in Ar gas of intense femtosecond beams with different transverse modes have shown that the cross-sectional profile of the laser beam in Bessel modes remains undistorted\textsuperscript{26} during propagation, and the outer part of the Bessel beam serves as an energy reservoir for the filament that is formed around the central portion of the beam.\textsuperscript{27} In addition, Scheller and colleagues have experimentally shown that the propagation of a femtosecond laser filament in air can be substantially extended by an appropriate use of a surrounding auxiliary dressing beam, continuously supplying energy to the filament.\textsuperscript{28}

In most of the related works, a conical lens called axicon is employed to generate a quasi-Bessel beam which is not collimated, and this makes the data analysis and interpretation more complicated. However, with that approach it was not possible to investigate the effect of the number of lateral lobes of a Bessel beam on the propagation of filaments, either. We formed a collimated Bessel-Gaussian beam with arbitrary number of lateral lobes by using a spatial light modulator (SLM) and a computer generated hologram (CGH) technique. This novel and universal approach enables the formation of arbitrary beam modes and is ideally suited for the main goal of this study, namely to investigate the influence of the mode structure of the Bessel beams on the formation and propagation of filaments. In order to study the influence of the mode structure of the incident Bessel-Gaussian beams on their propagation we experimentally investigate filament propagation dynamics in water of intense femtosecond pulses with Bessel-Gaussian beam profiles and different numbers of radial modal lobes under the condition of similar peak intensities, pulse durations, and diameters of the central peak of the beams. The choice of water as a nonlinear medium is dictated by its broad use and the fact that in liquids the Kerr nonlinearity is about three orders of magnitude larger than in gases,\textsuperscript{29} therefore the nonlinear effects develop on a shorter distance and require less laser power, which fits well our experimental conditions.

II. EXPERIMENTAL DETAILS, RESULTS AND DISCUSSION

The profile of an ideal Bessel beam is described by a zero-order Bessel function of the first kind which has a narrow main lobe surrounded by a decaying set of "side-lobe" rings.\textsuperscript{23} In our setup, the created transverse Bessel-Gaussian beams can be described by the following spatial distribution of the field amplitude: $E_{BG}(r, z = 0, t = 0) = E_0 J_0(\alpha r) e^{−\beta r^2}$, where $E_0$ is the peak amplitude, and $J_0$ is the zero order Bessel function. The constants $\alpha$ and $\beta$ are chosen in such a way as to make the central peak of the transverse mode create filaments, whereas the radial lobes have intensities too low to produce filamentation.

The input beam patterns were created from an initial Gaussian beam of a Ti:sapphire laser system (pulse duration of ~50 fs, central wavelength of 800 nm, and an output energy of 1 mJ per pulse at a 1 kHz repetition rate) by using computer generated-holograms\textsuperscript{30} displayed on a liquid crystal spatial light modulator (Hamamatsu LCOS-SLM X10468-2). The SLM had a resolution of 800x600 pixels (16 mm x 12 mm), and a maximum reflectivity of >95% for radiation between 750 nm and 850 nm. Figure 1 shows an illustration of the experimental setup used. The laser beam illuminates the SLM with a phase-amplitude encoded hologram set by a computer to produce a desired optical beam in the 1st diffraction order. Such grayscale computer-generated holograms for Bessel-Gaussian beams, prepared with a MATLAB code, were displayed on the LCD of the SLM via a digital visual interface connection. An illustration of the computer-generated hologram used to produce a Bessel-Gaussian beam in the first diffraction order is shown in the inset of Fig. 1. We note that the SLM creates a quasi-Bessel amplitude-phase distribution that together with the Gaussian distribution of the incident beam produces a Bessel-Gaussian beam, which has a limited cross section and a finite number of lobes. With all optical losses, including losses from the SLM, which employs off-axis holography to generate the beam modes, the incident power of the Bessel-Gaussian beam mode with a 300 μm diameter at FWHM in the central Gaussian counterpart at the entrance of the cell was measured as 55 mW. Consequently, for the repetition rate of our laser system (1 kHz) and the pulse duration (~50 fs), we obtained an input peak power of ~1.1 GW per pulse for the central lobe of the Bessel-Gaussian beam.
FIG. 1. Experimental setup: SLM, spatial light modulator; SP, syringe pump; GC, glass cell with an optical window; FG, flat glass; IR-F, infrared filter (which can be complimented by a neutral density filter) to measure the incident beam; PM, power meter; SM, spectrometer. The image next to the SLM is an example hologram used to create a Bessel-Gaussian beam. The image on the right shows a Bessel-Gaussian beam with filaments in the central part; it was taken with a color CCD camera using necessary filters and attenuators.

When the initial power in the produced optical beam exceeds the critical value for the optical medium, nonlinear optical self-focusing effect becomes important. Condensed transparent materials serve as efficient media for producing femtosecond filaments, which are sustained by the dynamic balance of Kerr self-focusing and defocusing due to plasma generation combined with energy losses resulting from nonlinear effects. The chromatic dispersion and self-steepening can be also important factors able to modify the pulse spectrum and intensity. To assess the influence of the group velocity dispersion (GVD) in water on the beam dynamics we estimated the dispersion length $L_d = \tau^2/((\partial^2 k/\partial^2 \omega) = 5 \text{ cm with } \tau = 50 \text{ fs and } GVD = (\partial^2 k/\partial^2 \omega) = 2.5 \times 10^4 \text{ fs}^2/\text{m.}$ Since this length is significantly longer than the self-focusing length $\sim 2 \text{ cm for the central peak of the incident beam, the dispersion should play comparatively minor role at our conditions. Also other nonlinear processes (like multiphoton absorption) can contribute to balancing the nonlinear effects for filament stabilization until the energy of the pulse is depleted.}

The peak power of the central lobe of the Bessel-Gaussian beams incident on the water surface was adjusted to a much larger value than the critical power for self-focusing in water, assuring the filament formation in water within the water cell, as was observed previously. Indeed, hot spots in the central part of the beam corresponding to filament formation were directly observed in our experiments, while the radial lobes had intensities too low to produce a filament as seen in the image of the inset of Fig. 1. We note that at the higher beam powers, which were avoided in our experiments, once the regime of multi-filamentation is reached, the beam energy quickly depletes, and filaments die out, since each filament dissipates energy at a similar rate. In addition to avoiding any undesirable beam break-up into multiple filaments, much care was also taken to ensure that the produced beams had central peaks with similar peak intensities, pulse durations, and beam diameters. The peak intensity and diameter were determined from the measurements with a power meter interchanged with a CCD camera; the measurements with the latter required additional neutral-density filters in front of it. We kept the distance between the SLM and the glass cell as short as possible to minimize the chromatic distortions due to diffraction gratings on the SLM. The beams were passed through a 13 cm-long glass cell, which was arranged vertically allowing us to measure the power and spectrum as a function of the propagation distance by changing the water level in the cell with
FIG. 2. Experimentally created modes of the incident Bessel-Gaussian beam registered with the CCD camera: (a) the central peak of the beam with no lobes and (b-h) the central peak with different number of additional radial lobes.

A programmable infuse/withdraw syringe pump (Harvard PHD 2000). A mechanical iris was used to select the central peak of the beam. An optical flat was positioned after the cell to reflect a small portion of the beam into the spectrometer. Spectral measurements were performed as a function of the propagation distance by collecting the radiation at the exit of the cell and analysing it with an Ocean Optics USB-2000 spectrometer. Simultaneously, laser power measurements were taken using a photodiode power meter head (Ophir PD300-IR) with a spectral range within 700-1800 nm. In order to measure the beam power after the water cell, a long-pass glass filter (RG-780) was placed in front of the power meter to filter out white-light. A LabVIEW code was used to control the infusing and withdrawing of water via a syringe pump and to acquire the values from the power meter and the spectrometer.

To understand the propagation of Bessel-Gaussian beams of different mode structure, we investigated their propagation dynamics by varying the number of radial lobes. Figure 2 depicts the experimentally created modes of the incident Bessel-Gaussian beam registered with the CCD camera. Figure 3 shows the comparison of the distributions of the laser intensity in the central part of the beams registered at different propagation distances for a beam with only the central lobe and for a Bessel-Gaussian beam, which has also 7 radial lobes. The distributions were measured with a monochromatic CCD camera and the generated white-light was filtered out by using RG-780 filter. The self-focusing effect took place near the entrance of the beam into the cell, and the changes of the beams with different number of radial lobes with the propagation distance in water were observed. The filaments formed by the incident beam with only the central peak exhibit faster decay as the pulse propagates than the filaments formed by the incident Bessel-Gaussian beam with radial lobes.

We also performed power and spectral measurements for only the central peak of Bessel-Gaussian beams with different number of radial lobes. The FWHM diameter of 300 μm of the central peak of the Bessel-Gaussian beam was selected by the mechanical iris positioned after the water cell in front of the power meter or spectrometer for spectral measurements. The spectral distributions measured as a function of the propagation distance are shown in Fig. 4(a). The effect of increasing number of radial lobes can be seen by an increase in the propagation distance of the central filament-containing peak of the beam. The increments of this increase are most noticeable, when 1, 2 or 3 lobes are added.

In Fig. 4(b), we show the infrared power measured for only the central peak of Bessel-Gaussian beams with different number of radial lobes as a function of the propagation distance. With each additional radial lobe we observe the trend of an increasing power delivered to a given propagation distance. At intermediate distances 6-9 cm the beams with multiple lobes (>2) show a significantly
FIG. 3. Measured IR distributions of the laser intensity (shown with false colors) of the beams at different propagation distances $z$: (a) a beam with only the central lobe is used and (b) a Bessel-Gaussian beam with the central and 7 radial lobes was produced at the entrance of the cell. The sharp intensity peaks, corresponding to formed filaments are clearly visible. These peaks are sustained for longer distances for the Bessel-Gaussian beam with radial lobes (case (b)).

slower rate of the power decrease compared to the beams with small number of lobes (1-2). At larger distances (>6cm) the delivered power decreases faster, and while the beams with multiple lobes show increased power decay rate, they maintain a higher power, as compared to the beams with smaller number of lobes.

The trend of a filament elongation was recently demonstrated experimentally by using dressed beams, where the central Gaussian beam is surrounded by an auxiliary dressing beam, which is wider and has a lower intensity. Since a Bessel-like beam, which has an annular structure, possesses an inward energy flux towards its optical axis, it is expected to be well suited to replenish the filament core, as is confirmed by our measurements. Also, when we compare our results with recent theoretical studies on filamentation of femtosecond beams with different transverse modes in Ar gas, we see a similar effect that the central filament-containing core in a Bessel-Gaussian beam mode with lateral lobes is sustained for a longer propagation distance (compared to a beam with only the central peak or a Gaussian beam). By extending the outer part of a Bessel-Gaussian beam we have shown how addition of radial lobes helps to maintain the energy in the central peak, thus demonstrating that this outer part serves as an energy reservoir for the filaments formed in the central portion of the beam.

FIG. 4. Spectra (a) and average IR power (b) of the central peak of the Bessel-Gaussian beams with different number of radial lobes measured as a function of the propagation distance.
III. CONCLUSION

We have studied the influence of the beam mode structure of intense femtosecond laser pulses on the filament propagation length in water. With the computer-generated hologram technique and a spatial light modulator we were able to create collimated Bessel-Gaussian beam modes with the outer part consisting of different number of radial lobes and investigated how the extension of this outer part helps to sustain the filaments in the central part of the beam during the propagation process. We have found that by increasing the number of outer radial lobes of Bessel-Gaussian beams (provided that the characteristics of the central part of the beam, such as the peak intensity, pulse duration, and beam diameter stay the same) contributes to maintaining the central intensity peak with filaments, and thus these additional lobes serve as energy reservoir for the central portion of the beam. Our findings demonstrate the high potential of Bessel-Gaussian beams for various nonlinear optics applications involving the extended propagation of filaments formed by ultrafast pulses in a Kerr medium.

ACKNOWLEDGMENTS

This publication was made possible by the NPRP award [NPRP 5-994-1-172] from the Qatar National Research Fund (a member of The Qatar Foundation). The authors would also like to express their appreciation to Robert A. Welch Foundation (Grant No. A1546) as well as Turkey’s Ministry of National Education. The statements made herein are solely the responsibility of the authors.

27. Z. Song and T. Nakajima, Optics Express 18, 12923 (2010).
34 Y. Coello, B. Xu, T. L. Miller, V. V. Lozovoy, and M. Dantus, Applied Optics 46, 8394 (2007).