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**Optical Wavepackets (Optical Bullets): A New Diffraction
Free Form of Light Travel**

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Optical Wavepackets (Optical Bullets): A New Diffraction Free Form of Light Travel

David J. Funk*, Jeff Nicholson, Xin Miao Zhao, Charlie E. M. Strauss, Antoinette J. Taylor, Jeffrey P. Roberts, R. Jason Jones (UNM)

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). We conducted studies of the propagation of self-confined packets of light or "Optical Bullets" through air. These packets are self-forming and require no active optics. At the present time, theoretical explanations provide an incomplete description of this process. Generation of these pulses requires a light source of sufficient energy and with a short enough pulse-width that the intensity exceeds a critical wavelength dependent value. We used a Ti:Sapphire based system to generate the pulses and we observed pulse-splitting and chirp-dependent control of the formation of these filaments. In addition, we developed a novel algorithm for extracting the phase and electric field of these pulses using Frequency Resolved Optical Gating coupled to genetic algorithms for pulse retrieval.

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Background and Research Objectives

A remarkable new form of light travel has been observed in the propagation of high power ($\sim 100\text{GW}$) optical pulses through the air: When a light pulse intensity exceeds a critical value, the pulse will self-focus to a filament and then become self-trapped--the self-induced (non-linear) refraction exactly compensates the normal diffraction. This occurs without any guiding media (other than air) and these filaments may propagate virtually indefinitely through normal atmosphere without diverging. One of us (XMZ) propagated a filament at least 30 meters without significant diffraction--that was the full length of the laboratory.^{1,2} It is also believed that these wavepackets not only self-compensate diffraction but that they may also self-compensate dispersion and become trapped in all three dimensions, as solitons, thereby earning the nickname "optical bullets"³.

Clearly, nonlinear effects (i.e., the interaction of the electric field of the light and matter can not be described with linear equations) are overcoming diffraction, and self-phase modulation (the effect on the phase of the pulse that interacting nonlinearly with matter introduces) is balancing group velocity dispersion, but the specific origin of these effects is not understood and hotly debated.

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The phenomena is certainly richer than simple self-focusing (the Kerr effect) since that order of nonlinearity leads to filament collapse followed by divergence into a wide cone. Other higher order contributors to the nonlinearity are the creation of a plasma through multi-photon absorption and population of neutral multi-photon states. It is hypothesized that the Kerr effect is balanced by defocusing arising from electron index of refraction in the induced plasma. Theoretical studies have predicted that pulses can be trapped in all three dimensions in a medium with a nonlinear index positive to second order, negative to higher orders, and with some losses (e.g. multi-photon absorption or tunneling ionization)^{4,5,6,7}.

Our studies examined this phenomena in the laboratory using recently developed tools that allow us to examine the electric field envelope and phase as a function of laser power and laser pulse "pre-conditioning" (i.e., sign and magnitude of the chirp). This in turn assists in the development of rigorous theoretical models of the phenomena.

Importance to LANL's Science and Technology Base and National R&D Needs

Interest in the phenomena is sharpened by three qualitative observations. First, the intense pulse causes light to be emitted by the atmosphere, a possible source of species specific detection (nonlinear absorption; air has virtually no one-photon absorption leading to fluorescence at the wavelengths studied). Second, this emission appears to be preferentially guided backwards along the beam path towards the laser. Third, at intensities well above threshold for the phenomena, multiple filament form, each of which appears to be stable. The first two effects have ramifications for remote sensing while the third has ramifications for long distance power propagation.

Other intriguing and practical questions include whether this self stabilizing beam might also penetrate turbulent, hazy or scattering atmospheres, such as those found in storm clouds, smoggy cities and battlefield conditions. Could this be used as a drill to produce long, small diameter holes with unprecedented aspect ratios? Such holes might be used as neutron spectrometers, for minimally invasive package inspection or waste sampling, and dental microsurgery. Recently, one of us (XMZ), has shown that filaments can define a path for electrical avalanche discharge, potentially allowing stimulation and guiding of lightning discharges^{1,8} (In fact, the Japanese Central Research Institute of Electric Power Industry has invested millions of dollars in laser control of lightning and suppression).^{9,10}

Scientific Approach and Accomplishments

Since this is a new physical phenomenon, the initial goal of this proposal was to simply characterize it; the present picture of propagation is far from complete. Even though filaments have been observed to propagate without diffraction for 30 meters, there is no proof that they existed as single stable filaments. The filament beam could not be observed simultaneously at various locations along the path. There was also no experimental information about the temporal evolution of the pulse. Furthermore, a strong power law dependence on wavelength would indicate that long wavelength filaments may arise from different contributing physical mechanisms than shorter wavelengths--yet both appear to be stable^{1,11,12}.

Using a Ti:Sapphire laser system, capable of 20 mJ/pulse in 150 fs, we successfully

- generated filaments,
- set up a frequency-resolved, optical-gating analysis station,¹³
- measured the energy in the filament as a function of travel distance in the laboratory (see Publication 1 for details),
- examined the effect of chirp on the pulse (both filament formation distance and on conical emission; see Publication 1 for details), and
- spectrally dispersed the filament and measured its auto-correlation as a function of distance traveled in the laboratory (see Publication 1 for details).

We demonstrated that the initial chirp played a large effect on the filament formation distance (Figure 1). We have also found that the pulse splits into two pulses as it propagates and as predicted by various theories that fold in the nonlinear interaction of intense electromagnetic fields with matter. We also found that the chirp played a large role in controlling the position of the pulse splitting (Figure 2). One goal is to be able to control this phenomenon and turn it into a useful tool for controlling lightning discharge (as an example) by providing an ionization path for the discharge. Our initial experiments demonstrated that such a goal may be achievable.

In addition to the data described above, we were able to obtain Frequency Resolved Optical Gated (FROG) data as a function of distance and chirp and use previously published algorithms to analyze the data and retrieve the electric field and phase of "split" pulses as shown in Figures 3 and 4.

Finally, we developed a new algorithm to analyze FROG data based on a genetic algorithm, details of which can be found in Publication 2. An overview of the algorithm is

shown in Figure 5, with an example of the reconstructed field for Second Harmonic Generation FROG (SHG-FROG) shown in Figure 6.

Publications

1. Zhao, X. M., Jones, R. J., Funk, D. J., Strauss, C.E.M., Roberts, J. P., and Taylor, A. J., "Evolution Characteristics and Control of Self-Filamentation in the Atmosphere," submitted to Opt. Lett. (1997).
2. Nicholson, J. W., Funk, D. J., Omnetto, F. G., and Taylor, A. J., "Evolving Frogs: Phase Retrieval from Frequency-Resolved Optical Gating Measurements using Genetic Algorithms", to appear in Opt. Lett., 1999.

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Figure 1. Effect of chirp on filament formation distance. The graph shows that the pulse forms most readily when blue light precedes red light (large $\Delta l/l_d$) as expected from a simple, group-velocity dispersion analysis.

Figure 2. Effect of chirp on pulse splitting as a function of propagation distance L . The graph shows that the pulse splits most readily when blue light precedes red light (large $\Delta l/l_d$) as expected from a simple self-phase modulation and group velocity dispersion analysis.

Figure 3. FROG data (left) and reconstruction (right) of a split pulse originating with no chirp and located 11.9 m from the laser.

Figure 4. Reconstructed electric fields and phase for a pulse that it isn't split (3.4 m from laser; left) and a pulse that has begun splitting (11.9 m from laser; right)

Figure 5. Schematic of the genetic algorithm (GA).

Figure 6. Comparison of the reconstructed SHG-FROG data between previously published composite algorithms and our novel GA.