Secondary Radiation Generation Using High-Intensity Short-Pulse Lasers

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Abstract— **During propagation in air, high-intensity laser pulses can convert some of their energy into frequencies far from the laser fundamental, simultaneously covering microwaves to the ultraviolet. We present recent progress to understand the mechanisms responsible for low-frequency secondary radiation, and how this may inform designs for next-generation short-pulse lasers.**

Keywords—nonlinear optics, lasers, ionization, plasma, microwaves, terahertz

I. Introduction

There are several emerging applications involving the propagation of high-intensity lasers having pulse durations in the picosecond to femtosecond range. The regime of laser-matter interaction accessible with intense, short pulses is inherently nonlinear, including optical field ionization that occurs simultaneously with many intensity-dependent aspects of the medium's bound electron response. One important consequence of the nonlinearities is that the pulses are able to convert a portion of their energy into secondary radiation through firmly understood nonlinear optical mechanisms (e.g. self-phase modulation, three or four wave mixing including harmonic generation, etc.) as well as more recently explored low-frequency emissions in the microwave [1], terahertz (THz) [2] and far infrared [3] ranges. The dominant sources of the low-frequency radiation result from interaction of the laser field with the plasma it creates during propagation.

We present our recent work to understand the physical mechanisms responsible for generating the microwave emission from laser-produced plasmas in gases, typically air. THz secondary radiation from air plasmas provides a useful point of comparison as it has been investigated thoroughly [2,4] particularly for the case of a two-color input laser pulse, where the laser fundamental and its second harmonic are coherently superimposed [5]. For single-color laser pulses, the plasma currents which produce the microwaves versus the THz are distinct. The microwaves arise from longitudinally coherent, transverse excursions of electrons in the high-energy tail of the energy distribution function at the plasma-gas boundary [6], whereas the THz radiation comes from longitudinal currents stimulated by the laser ponderomotive force [7].

With two-color laser pulses, the photocurrent mechanism predicts THz generation resulting from temporal asymmetry of electron trajectories in the laser field [8]. The THz power from an optimally phased two-color pulse is about 1000 times greater than a single-color pulse of the same energy and peak intensity [5]. Our recent experiments measuring microwave generation with two-color pulses show behavior that is different from the single-color case, and also that photocurrents may not be the principal microwave radiation source.

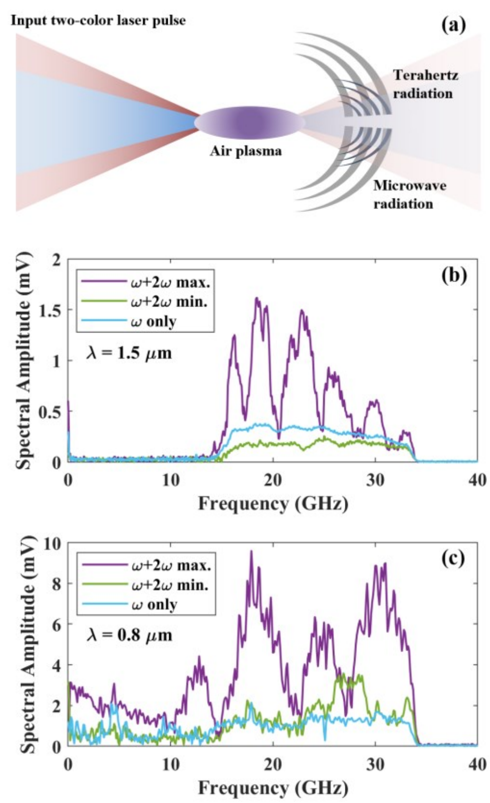

Fig. 1. (a) A two-color laser pulse comes to focus and creates an air plasma that radiates microwaves and THz with a conical angular pattern. Example frequency spectra of the microwave radiation from two-color laser pulses for fundamental wavelengths of (b) 1.5 μm and (c) 0.8 μm are compared for the cases of two-color relative phase that maximize and minimize the microwave field strength, along with the spectrum resulting from a single-color laser pulse.

II. Results and Discussion

Figure 1(a) depicts the laser interaction in concept, with the secondary radiation fields propagating from the plasma

This work is supported by the NRL Base Program. This material is based on work supported by the National Science Foundation MPS-Ascend Postdoctoral Fellowship under Grant No. 2213242.

distributed angularly in a cone oriented in the forward direction (indicating plasma currents that flow longitudinally) as a short-duration, broadband pulse. We present an example of how a few of the input laser pulse characteristics change the microwave radiation amplitude and frequency spectrum. The laser wavelength, the two-color relative phase, and the laser pulse duration all significantly influence the initial conditions of the electron population. The frequency spectra in Fig. 1 demonstrate that each of these has an effect on the amplitude and frequency content of the microwaves. The purpose of the work is to ascertain how the aspects of the laser pulse which influence the ionization rate, electron trajectories, and total energy deposition in the plasma map to features of the microwave and THz fields that we can measure.

The experiments often require use of multiple laser systems in order to cover the parameter space of interest. In Figs. 1(b) and 1(c) we show frequency spectra radiated from two-color laser-produced air plasmas generated with a 1 ps, 0.8+1.5 μm pulse from a high-energy optical parametric amplifier (OPA), and a 50 fs, 0.4+0.8 μm Ti:Sapphire pulse. It is possible to control the relative phase between the fundamental and second harmonic waves by adding group delay dispersion to the laser harmonics. This reshapes the laser electric field waveform, causing large changes in the microwave radiation amplitude and spectrum.

It is necessary to use broadband receivers to measure the microwaves, as their pulse duration is a few field cycles at most. This may be done with a pyramidal horn antenna, as is the case in Fig. 1(b), or an electric field (d-dot) probe, such as in Fig. 1(c). The latter can be convenient as they do not possess a low-frequency cutoff like a waveguide-based structure, however their effective aperture is orders of magnitude smaller than a typical antenna. In both cases, the electric field waveforms are directly digitized with a fast oscilloscope that has a bandwidth of 33 GHz. The frequency spectra in Figs. 1(b) and 1(c) are the Fourier transform of the time domain voltage traces that the oscilloscope records.

For both laser wavelengths, there is a particular harmonic relative phase that maximizes the radiated microwave amplitude. In this case, the peak microwave field is about 3 times greater than if we used a single-color laser pulse. The most interesting features of the maximized spectra are the modulations that are present for both the 0.8 μm and 1.5 μm laser wavelengths that vanish if the relative phase is detuned. The modulations imply the existence of multiple pulses in the time domain, and are not explained by the mechanism that describes single-color microwave generation, which predicts nearly transform-limited secondary radiation pulses [6]. It is important to note that the frequency spacing of the modulations is smaller at 1.5 μm than 0.8 μm. This could be due either to the change in laser wavelength, pulse duration, or a consequence of the transfer functions of the different microwave receivers. Another difference between Figs. 1(b) and 1(c) is that the harmonic relative phase that minimizes the microwave field strength at 0.8 μm gives a spectrum that is similar in content and amplitude to that produced by a single-color 0.8 μm laser pulse. However, at 1.5 μm the minimizing harmonic relative phase reduces the microwave amplitude a small amount below that of the single-color case.

Explaining these differences in the secondary radiation spectra is the focus of our ongoing work, as it will allow us to infer the electron kinetics occurring early in the plasma lifetime. Additional experimental diagnostics will complete the physical picture in addition to simulations of the laser propagation and plasma evolution. We can correlate the microwave amplitude and spectra with those of the THz radiation, and also the optical supercontinuum and harmonics, all of which are sensitive to the format of the input laser pulse including whether it is single-color or two-color.

III. Conclusion

Exercising any degree of control over laser-plasma interactions during propagation in a gas is difficult because of the variety of phenomena that result from the interaction over timescales ranging from shorter than the laser pulse duration to a few orders of magnitude longer, their highly nonlinear dependence on the laser intensity, and also on several other factors, a few of which we have highlighted here (such as laser wavelength and pulse duration). The goal is to understand the laser-plasma interaction so that we might achieve the control necessary for the success of an application, and thus inform the proper laser pulse format to employ, which includes the overall design of the laser source. The secondary radiation is one of the only non-invasive options that may be able to capture the plasma behavior in the intermediate timescale when its dynamics are the most complex. That is the period between the initial ionization events, and long-term equilibration of the plasma before its recombination. Ultimately, studies of the secondary radiation lead to questions about how a laser field with generalized characteristics imparts energy to the plasma electrons. In particular, the sequence of events is not understood in which electrons acquire residual energy and redistribute it over time within the weakly ionized plasma produced in our experiments.

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