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Photon Acceleration via Laser-Produced Ionization Fronts

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Abstract. Microwave radiation has been upshifted in frequency and compressed in duration by more than a factor of five via its interaction with a relativistically propagating, underdense ionization front. The experimental observations are in good agreement with theoretical predictions.

1. Introduction

When a pulse of electromagnetic radiation reflects from a moving mirror, its frequency and duration are altered by the relativistic Doppler effect. For an approaching mirror the frequency increases and the pulsewidth decreases by a factor of $(1+\beta)/(1-\beta)$, where β is the velocity of the mirror divided by the speed of light in vacuum, c. It has been proposed that a similar frequency shift and temporal compression would occur upon reflection from a rapidly-propagating ionization front. An ionization front is simply a boundary between a region of neutral gas and a region of plasma. This type of boundary is produced when an ionizing laser pulse propagates through a volume of neutral gas. Unlike a physical mirror, the velocity of a laser-produced ionization front can be very close to c. Thus if incident radiation were reflected from such a front it would be upshifted by many orders of magnitude [1].

In general, electromagnetic radiation of frequency ω_0 will be reflected from a plasma boundary if $\omega_p > \omega_0$ (an overdense plasma) and will be transmitted through the boundary if $\omega_p < \omega_0$ (an underdense plasma). Here ω_p is the characteristic plasma frequency which is given by $\omega_p \approx 2\pi \times 9000\sqrt{n}$, where n is the plasma density in cm^{-3}. In order to determine whether an ionization front will reflect or transmit incident radiation, one must compare the plasma and radiation frequencies in the rest frame of the ionization front. In this frame the radiation frequency is greater by a factor of $[(1+\beta)/(1-\beta)]^{1/2}$ but the plasma frequency, which is Lorentz invariant, is unchanged. Thus extremely large plasma densities are required for a highly relativistic front to be overdense.

However, it has recently been proposed [2] and experimentally confirmed [3] that even when the front is underdense, large frequency upshifts and temporal compressions may be observed. In this case the radiation is transmitted into the plasma, and because the boundary is moving, its frequency is upshifted. For highly relativistic fronts the upshift is given by $\omega_{up} \approx \omega_0(1+\omega_p^2/4\omega_0^2)$.

2. Experiment

Our experimental arrangement is shown in Fig. 1. Microwave radiation is fed into a straight section of WR-19 waveguide through a 3dB directional coupler. The waveguide is sealed at each end with 0.1 mm-thick quartz windows which, because they are much less than a wavelength in thickness, reflect very little of the microwave radiation. The guide is evacuated and filled with azulene (chosen because it is easily ionized by

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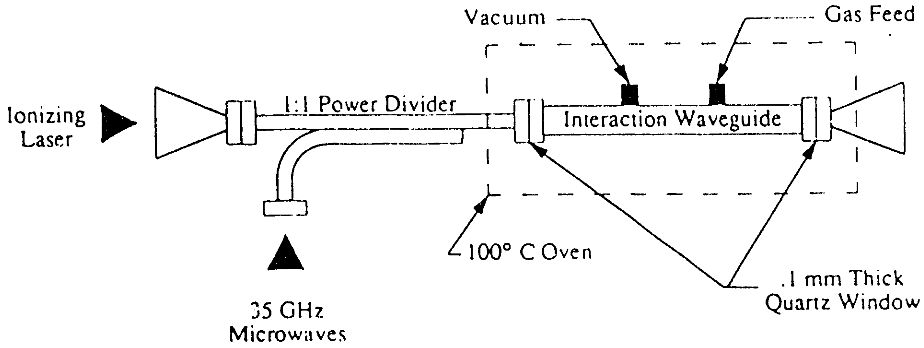
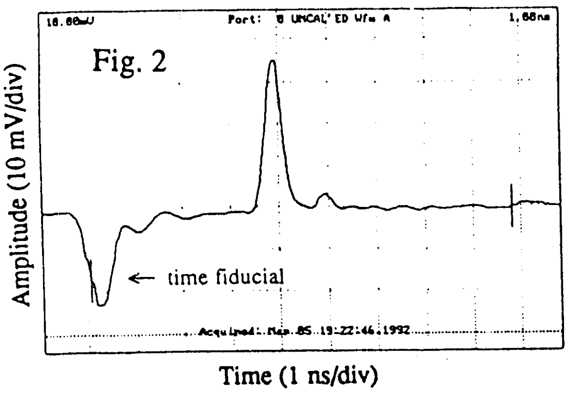


Figure 1: Schematic of experimental set-up.



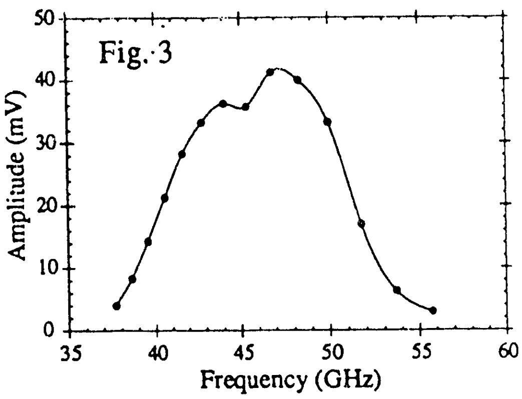
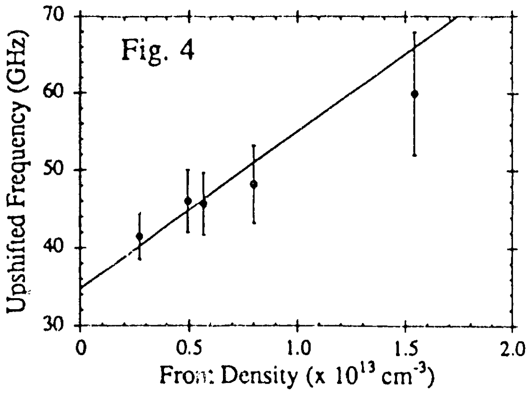


Figure 2: Temporal width of upshifted radiation for a front density of 8×10^{13} cm^{-3}.
Figure 3: Frequency spectrum of upshifted radiation for a front density of 5×10^{12} cm^{-3}.

266 nm radiation) vapor at pressures of up to a few hundred millitorr. The microwave source is a 35 GHz pulsed magnetron with a peak power of 10 kW and a pulsewidth of 300 ns. A highly relativistic ionization front is created by photo-ionization as a laser pulse (40 mJ, 50 ps, 266 nm) propagates down the azulene-filled waveguide. This front overtakes the slower-traveling microwaves which propagate at 0.4c in the WR-19 waveguide. Theory predicts that the frequency shift will be proportional to the plasma density of the front. Also, because the upshifted radiation propagates at a higher velocity (hence the term "photon acceleration"), the overtaken wave is compressed in duration.

Fig. 2 shows the temporal evolution of a typical upshifted pulse recorded using a broadband diode detector and a 1 GHz bandwidth oscilloscope. This pulse was upshifted from 35 GHz to over 174 GHz (measured using a cutoff waveguide) and compressed to less than 0.4 ns in duration . The spectra of the upshifted pulses were measured using a microwave diffraction grating. Fig. 3 shows an upshifted spectrum for an ionization front density of 5×10^{12} cm^{-3} (measured using a microwave interferometer).

Fig. 4 shows the center frequency of the upshifted spectra plotted vs. front density.



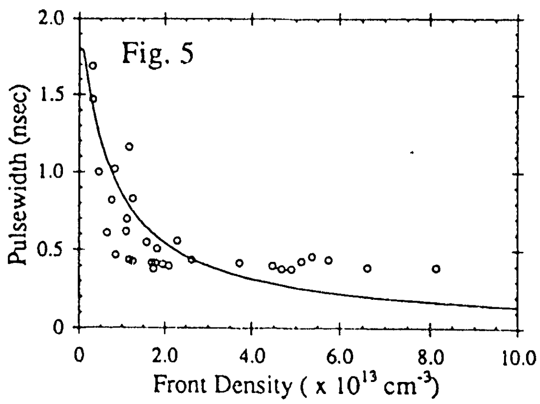


Figure 4: Measured upshifted frequencies vs. front density. Figure 5: Measured upshifted pulsewidths vs. front density. The solid lines are the theoretical predictions.

The error bars represent the widths of the measured spectra (FWHM) and the solid line is the theoretical prediction. Fig. 5 shows the upshifted signal pulsewidths as a function of front density plotted with the theory curve. The points at higher densities are detector-limited to $\sim$ 0.4 ns.

3. Conclusions

By sending an intense ionizing laser pulse through a cavity of neutral azulene gas, we created a relativistically propagating, underdense ionization front. When this front impinged upon a train of microwaves, we observed large (up to a factor of five) frequency upshifts and pulse compressions. By varying the neutral gas pressure (and thus the front density), we continuously tuned the frequency and pulsewidth of the upshifted radiation. We expect that broadly tunable sources based on this technique will have many applications, including time-resolved spectroscopy. By utilizing higher frequency source radiation and higher density ionization fronts this technique has the potential to provide a new class of tunable, short pulse, coherent radiation sources operating from the microwave regime to the vacuum ultra-violet.

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