GENERATION OF HIGHLY TUNABLE MICROWAVE RADIATION VIA A RELATIVISTIC IONIZATION FRONT

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ABSTRACT

This paper reports the experimental demonstration of frequency upshifting of microwave radiation by a relativistic ionization front. Source radiation at 34.8 GHz has been upshifted to greater than 116 GHz in a continuously tunable fashion. It is a new technique for generating high-power, tunable radiation in short pulses, and has potential applications in plasma diagnostics, time-resolved microwave spectroscopy and ultra-wideband impulse radar.

INTRODUCTION

When an intense, ionizing laser pulse passes through a column of neutral gas, a sharp boundary can exist between the freshly created plasma and the unionized gas. This boundary, or ionization front, propagates at the velocity of the laser light in the plasma. Semenova [1] and Lampe et al. [2] have proposed that if the plasma were overdense [3], then an electromagnetic wave impinging on such an ionization front would be reflected and have its frequency and duration altered by the familiar relativistic Doppler effect ($\omega/\omega_0 = \Delta t_0/\Delta t = \gamma^2(1+\beta)^2$) [4]. With existing laser technology, it would be difficult to create such a dense plasma by photo-ionization, but W. B. Mori [5] has recently shown that large frequency upshifts and associated pulse compressions are possible even when the plasma created by the front is underdense.

We have experimentally confirmed Mori's predictions by passing a 50 psec long ultraviolet laser pulse through a resonant microwave cavity operating near cutoff, such that the group velocity of the microwaves is significantly less than that of the front. The front thus encounters both co- propagating and counter- propagating radiation. Upshifts to greater than three times the source frequency have been obtained with pulse widths of less than 1 nsec.

THEORY

The theroetical treatment of the rapid variation of the refractive index, which causes the frequency of the radiation to upshift, is most easily carried out by making a Lorentz transformation into the rest frame of the front, and proceeds as follows: Consider counterpropagating microwave radiation at frequency ω which is confined in a cylindrical cavity that is filled with neutral gas. A short, intense, ionizing laser pulse enters one end of the cylinder and passes through the cavity creating an ionization front that propagates at the group velocity of the ionizing radiation in the plasma it has created, v_g. The relativistic Lorentz factor, γ, for the front is given by $\gamma = (1-\beta^2)^{-1/2}$ where $\beta = v_g/c$ with c being the speed of light in vacuum. The standing wave in the cavity can be decomposed into a wave propagating in the same direction as the laser pulse, which we call the *forward* wave, and one counterpropagating which we label the *backward* wave. Before the arrival of the laser pulse, the forward and backward radiation have the same frequency, $\omega_f = \omega_b = \omega$, and the magnitude of their oppositely directed wave vectors is determined by the dispersion relation for electromagnetic radiation in the cylindrical waveguide, $\omega^2 = \omega_c^2 + c^2 k_{f,b}^2$, where ω_c is the cutoff frequency for the particular operating mode. They both propagate at the group velocity, $v_g = c(1-\omega_c^2/\omega^2)^{1/2}$, which can be significantly less than c for ω close to ω_c. By performing a Lorentz transformation, we obtain the frequencies of the waves in the rest frame of the ionization front, $\omega'_{\substack{f\\b}} = \omega\gamma(1 \mp \beta v_g/c)$. In this frame the front is a stationary boundary with neutral gas flowing towards it on one side and plasma streaming away from it on the other side. The plasma frequency, ω_p, which is invariant under Lorentz transformations, is given by $\omega_p^2 = 4\pi n_0 e^2/m$ where n_0 is the plasma density, m is the electron mass, and e is the electron's charge. If the density of the front is such that $\omega_p << \omega'_{f,b}$, then it is underdense and the radiation at $\omega'_{f,b}$ will be transmitted into it (when $v_g < v_{front}$ the forward wave will be overtaken by the front, and thus propagate into it). As with any stationary boundary problem, the transmitted radiation will have the same frequency as the incident radiation, but its wave vector will adjust to obey the dispersion relation for electromagnetic radiation in the streaming plasma, namely $\omega'^2_{p_{f,b}} = \omega_c^2 + \omega_p^2 + c^2 k'^2_{p_{f,b}}$. The subscript p denotes inside the plasma, while the superscript $'$ denotes in the front's rest frame. Thus, inside the plasma in the front's frame we have $\omega'_{p_{f,b}} = \omega'_{f,b}$ and $k'_{p_{f,b}} = 1/c(\omega'^2_{f,b} - \omega_c^2 - \omega_p^2)^{1/2}$. We are interested in the frequencies of the upshifted radia-

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tion in the laboratory frame, so we now Lorentz transform back and obtain

$$\omega_{p_{f \atop b}} = \omega\gamma^2(1 \mp \beta v_g/c)\left\{1-\beta\left(1-\frac{\omega_c^2+\omega_p^2}{\omega^2\gamma^2(1\mp\beta v_g/c)^2}\right)^{1/2}\right\}. \tag{1}$$

The theoretical values for the upshifted frequencies of the forward and backward waves predicted by Eq. 1 are plotted

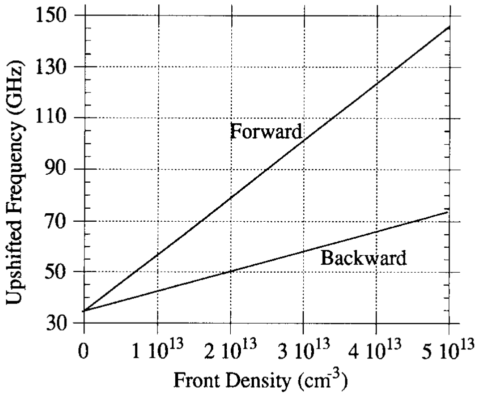

Figure 1: Upshifted frequencies of the *forward* and *backward* waves vs. the front's plasma density for 34.8 GHz source radiation.

in Fig. 1 as a function of the front density for source radiation at 34.8 GHz. For a given plasma density the forward-propagating radiation is always upshifted by a larger amount than the backward-propagating radiation. In Fig. 2 we plot the absolute value of the group velocity of the upshifted radiation as a function of front density. One sees that as the degree of upshift increases, the group velocity of the forward wave steadily increases, while that of the backward wave decreases to zero at the point where $\omega_c^2+\omega_p^2 = \omega(1+\beta v_g/c)$. As the front density, and thus ω_p, increases further, the initially backward propagating wave travels in the forward direction with a group velocity that approaches that of the forward wave for large upshifts.

EXPERIMENT

The experimental arrangement is shown schematically in Fig. 3. The microwave cavity consists of a copper cylinder 35 cm long and 1.2 cm in diameter which is closed by quartz windows at each end. Microwave radiation from a magnetron operating at 34.8 GHz (P_{peak} ~10 kW, pulse-length ~300 nsec) is coupled by rectangular guide through the side wall of the cavity and excites the TE_{01} mode. The measured Q of the cavity is aproximately 1000. The ionizing radiation is derived from a c.w. mode-locked Nd:YAG oscillator whose output is amplified in a Nd:YAG regenerative amplifier, then further amplified before two frequency doubling stages yielding 50 psec long, 40 mJ,.266 μm laser pulses at a 5 Hz repetition rate. The cavity is filled with 1-100 mTorr of azulene vapor, which is chosen because it is easily ionized by u.v. radiation. We use standard diode detectors preceded by sections of various waveguides that act as high-pass filters to observe the upshifted radiation. These detectors can be placed in either the forward or the backward directions and rotated about the cavity outputs in order to measure antenna patterns. The plane of polarization of the laser radiation is perpendicular to the surface of the laser table and thus perpendicular to the plane of the pattern scans

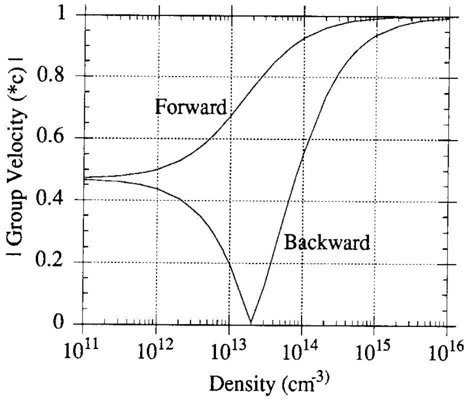

Figure 2: Absolute value of the group velocity of the *forward* and *backward* waves vs. the front's plasma density.

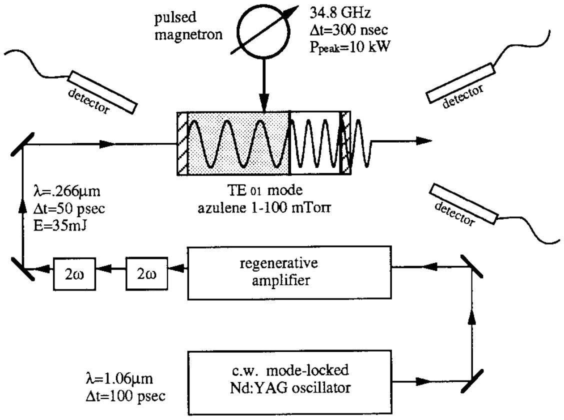

Figure 3: Schematic of the experimental arrangement.

as well. The detectors are placed with the narrow dimension of the waveguide perpendicular to the table surface.

The response of four detector channels at 40 GHz, 59 GHz, 91 GHz and 116 GHz are plotted versus pressure in Fig. 4. As the azulene pressure is increased, a point is reached where the front plasma density is high enough to upshift the radiation past the cutoff of the waveguide, and the signal increases sharply. The signal saturates, then decreases as the radiation is shifted to higher frequencies where the detector response falls off. The onset of the upshifted signal becomes less sharp at high frequencies, probably due mostly to laser pump depletion. A high speed Tektronix 7104 oscilloscope was used to recored the temporal duration of the upshifted radiation. A typical upshifted signal on the 59 GHz detector channel is shown in Fig. 5, where the horizontal axis is 500 psec per division. The FWHM of the pulse is less than 1 nsec. Fig. 6 shows that the "butterfly" antenna pattern of the TE_{01} mode is preserved for upshifts close to the source frequency (40 GHz channel), but becomes peaked on axis as the degree of upshift increases, as shown in Fig. 7 for the 91 GHz channel. When the laser is blocked, the total radiated power at the source frequency is approximately 5.8 kW. The total upshifted power in the forward direction at 40 GHz is approximately 3.1 kW. If we define the upshifted power efficiency as upshifted power radiated in the forward

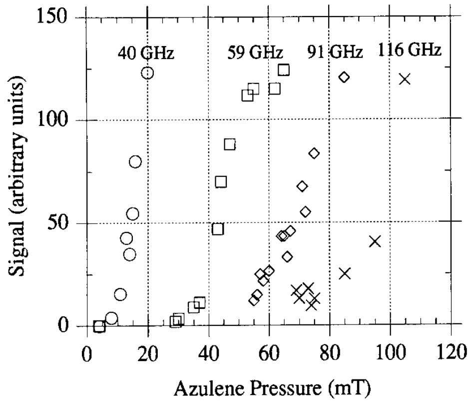

Figure 4: Onset of the upshifted signal vs. azulene pressure for the 40GHz, 59GHz, 91GHz, and 116GHz detector channels.

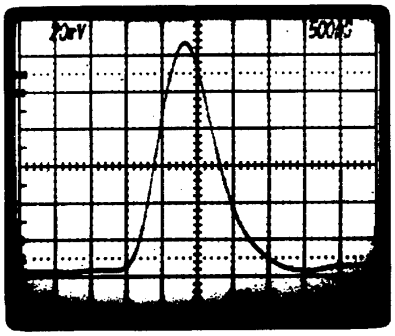

Figure 5: Temporal duration of a typical upshifted signal on the 59 GHz detector channel. The horizontal scale is 500 psec per division.

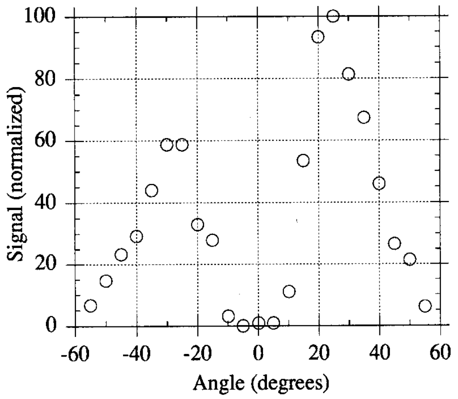

Figure 6: Antenna pattern of the upshifted radiation measured on the 40 GHz detector channel.

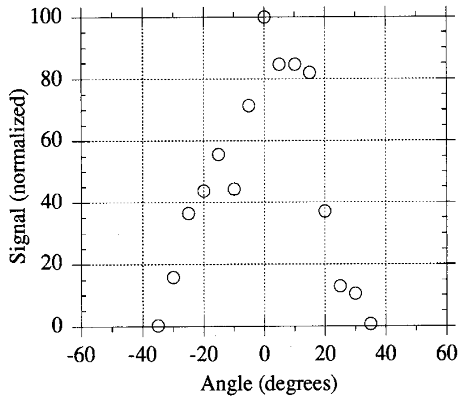

Figure 7: Antenna pattern of the upshifted radiation measured on the 91 GHz detector channel.

direction divided by the source radiation radiated in the forward direction with the laser blocked, the efficiency is greater than 50% at 40 GHz. Thus defined, the efficiency is only a fraction of a percent at 90 GHz where the forward radiated power is approximately 22 watts. This lower efficiency may be largely due to laser pump depletion along the cavity axis causing the length over which a sufficiently dense front is created to decrease.

CONCLUSIONS

In this paper we have presented a new method of continuously upshifting the frequency of an electromagnetic wave. This technique utilizes a relativistically propagating ionization front to simultaneously upshift and compress the source radiation. Using existing technology, it is possible to apply this technique to obtain a single source that is tunable from the microwave (30 GHz) to the millimeter (300 GHz) regime. Peak powers in the kilowatt range with pulse durations of much less than 1 nsec are feasible. Indeed, we have demonstrated this technique in a proof of principle experiment by upshifting 34.8 GHz radiation to greater than 116 GHz, with the degree of upshift being continuously tunable. It should be possible to scale the technique to higher frequencies and much higher powers.

The diverse potential applications for such a tunable short pulse source range from pure research to applied technology. For instance, the tunability could be very usefull in plasma density diagnostics with excellent spatial resolution and in time-resolved microwave spectroscopy. Other potential applications include device characterization, remote sensing, ultra wideband radar, and low observable radar cross sectin measurements.

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