Demonstration of Microwave Generation from a Static Field by a Relativistic Ionization Front in a Capacitor Array

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We present the results of a proof-of-principle experiment to demonstrate the generation of tunable radiation from a laser-ionized gas-filled capacitor array. This scheme directly converts a static electric field of wave number k_0 into coherent radiation pulses of frequency $\omega_p^2/2k_0c$, where ω_p is the plasma frequency. The radiation frequency can be tuned by varying gas pressure and/or capacitor spacing. In this experiment, well-polarized, short (less than 5 ns) microwave pulses have been generated over a frequency range of 6 to 21 GHz. The frequency of the detected signal, as measured with cut-off waveguides, scales linearly with the plasma density, and the relative power of the signal scales quadratically with the dc bias voltage in agreement with the theory. [S0031-9007(96)01789-9]

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High-power, ultrashort radiation sources play important roles in diverse applications ranging from advanced radar to ultrafast chemical and biological imaging, ultrafast interactions in solid state, atomic physics, etc. Most high-power conventional radiation sources are either free electron sources (e.g., free-electron lasers or gyrotrons) or laser/maser sources. In the past decade, a variety of alternate schemes have been proposed and pioneered [1]. One example is the use of a laser-produced ionization front to up-shift and pulse compress existing microwave radiation [2–4]. Recently, it was proposed to use a laser-produced ionization front to generate radiation directly from a static electric field [5], thereby eliminating the need for an initial high-power microwave source. In this scheme, called a dc to ac radiation converter or DARC source, radiation is up-shifted from zero frequency to a tunable value. In this Letter, results of a proof-of-principle experiment to test this mechanism are presented.

The geometry of the scheme is shown in Fig. 1. Alternately biased capacitors produce a static electric field of the form $E \approx E_0 \sin(k_0 x)_{\hat{y}}$ in a working gas, where $k_0 = \pi/d$ and d is the spacing between adjacent capacitor plates. The amplitude of the static field E_0 is approximately equal to V_0/b, where V_0 is the dc bias voltage and b $(b < d)$ is the gap between top and bottom plates. An ionization front (e.g., created by a short laser pulse with a pulse rise time typically much less than the device length divided by the speed of light) moves between the plates in the $+x$ direction with a laser group velocity $v_f = c(1 - \omega_p^2/\omega_L^2)^{1/2}$, where $\omega_p = 4pn_0e^2/m$ is the plasma frequency of the ionized gas and ω_L is the laser frequency. Since the ionization front changes the dielectric constant of the medium in both time and space, both ω and k of the "incident wave" field are shifted by the passage of the front (in this case, from $\omega_L = 0$ to a nonzero value).

To describe the radiation generated, it is convenient to consider the situation in a reference frame moving with the ionization front. In this frame, the Lorentz transformed electric field approximates an incident electromagnetic wave since the front velocity is close to the speed of light. The front is static in this frame, and the incident wave gives rise to reflected and multiple transmitted waves with a Doppler shifted frequency $\omega' = \gamma k_0 v_f$, where $\gamma = (1 - v_f^2/c^2)^{1/2}$. When transformed back to the laboratory frame, the reflected wave is an extremely short pulse of hard x rays with an amplitude approaching zero. One of the transmitted waves is an electromagnetic wave and the others are plasma oscillations or static magnetic modes. The transmitted radiation gives frequencies which can be tuned by varying the plasma density or capacitor spacing. The frequency is in the microwave to infrared range for practical capacitor geometries and plasma densities. The observation of this radiation is the focus of this Letter.

The frequency of the transmitted radiation can be easily obtained in the lab frame [5,6]. The frequency follows from two conditions: (i) the plasma dispersion relation and (ii) continuity conditions at the front boundary.

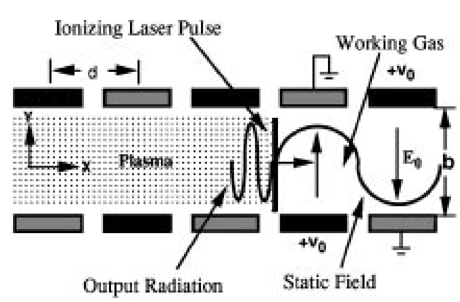

FIG. 1. Geometry of a dc to ac radiation converter.

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The dispersion relation is $\omega^2 = \omega_p^2 + k^2c^2$, while the equation for phase continuity is $\omega + kv_f = k_0 v_f$. When the front velocity is close to the speed of light (i.e., the laser frequency ω_l much greater than the plasma frequency ω_p), the output frequency can be approximated as [5]

$$\omega \approx k_0 v_f/2 + \omega_p^2/2k_0 v_f \, . \tag{1}$$

When the plasma frequency is high enough ($\omega_p > k_0 v_f$), it is found that large up-shift can occur, and this radiation actually moves in the same direction of the ionization front [5].

The output power of this transmitted mode can be calculated by finding the transmission and reflection coefficients at the ionization front boundary. The details of this calculation can be found in Ref. [5]. For relativistic fronts ($v_f \approx c$) and large up-shifts, the result for the transmission coefficient of the transmitted wave approaches one. That is, the output radiation has a field amplitude approximately equal to that of the static electric field. Therefore, the output power is approximately $P_{\text{out}} \approx E_0^2 V_g A/8\pi$, where V_g is the group velocity of the radiation in the plasma $[V_g = c(1 - \omega_p^2/\omega^2)^{1/2}]$ and A is the area of the ionization front. This can be expressed as an engineering formula of the form

$$P_{\text{out}} = 1.33 \text{ kW} \, \frac{V_g A}{cb^2}\left(\frac{V_0}{1 \text{ kV}}\right)^2 . \tag{2}$$

This power scaling law illustrates the potential of this scheme for producing high-power radiation.

The DARC source produces radiation pulses at a given frequency that are N half-cycles long, where N is the number of capacitors in the array. It thus has the potential to generate very short pulses.

An experiment was designed to test the theory for output frequencies in the microwave range. Figure 2 depicts the schematic of the experimental setup. A pyrex glass tube and two stainless steel flanges form the vacuum chamber which was evacuated by a turbomolecular pump. Two quartz windows provide the vacuum interface for the laser and microwave radiation. Azulene vapor was chosen to be the working gas because it is easily ionized by our 266 nm laser [4]. In order to achieve sufficient azulene vapor pressure, the entire experimental setup was wrapped with heating tape, and the experiment was operated at a temperature of 140 °C. At this temperature the chamber was pumped down to a background pressure of about 3 mTorr, and a leak valve was used to control the amount of azulene vapor leaking into the chamber and therefore the gas pressure. A convectron gauge was used to monitor the pressure in the chamber. The structure consists of 12 pairs of copper electrodes (6 periods) embedded in high temperature resistant plastic kel-F material. This material is mechanically stable and has high dielectric strength. The spacing between adjacent electrodes (d) was 4.7 cm with a plate separation (b) of 1.5 cm. This capacitor array was alternately biased with a dc power supply with an operating voltage between 100 V and 1 kV. The laser system produced an intense UV pulse (266 nm) with a 50 ps duration (FWHM), a spot diameter of 1 cm, and total energy of 30 mJ. The group velocity of the laser pulse in a 10^{12} cm^{-3} plasma is within 10^{-4}% of the speed of light. The microwave radiation was detected with the combination of a horn antenna followed by a matched waveguide and a crystal detector in various bands. Four specific bands were used, namely, the X band (with cutoff at $f_c = 6.56$ GHz), Ku band ($f_c = 9.49$ GHz), K band ($f_c = 14.08$ GHz), and Ka band ($f_c = 21.07$ GHz).

Figure 3 shows a typical output signal from the microwave detector on the oscilloscope, together with a laser signal produced by a photodiode placed at the entrance of the horn antenna. This microwave signal (the top reverse pulse) is coincident with the 50 ps laser signal (the bottom pulse). The fact that the microwave signal is prompt (except for an instrumental delay) and short in time suggests that the microwave signal was induced by the laser pulse. Tests showed that the appearance of this signal was directly associated with (1) the presence of azulene in the chamber, (2) dc bias on the capacitor plates, and (3) the ionizing laser. The signal was well polarized in the direction of the dc bias field, typically

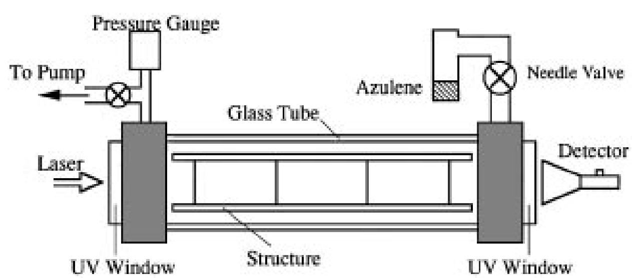

FIG. 2. Schematic of the experimental setup.

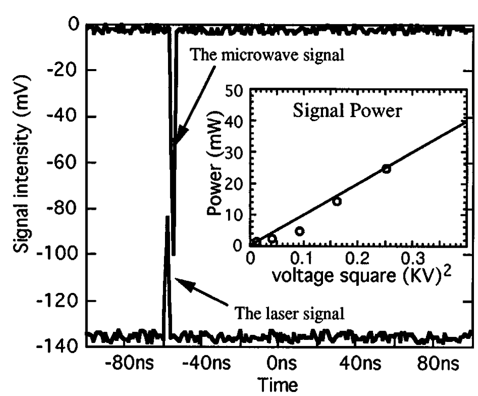

FIG. 3. The typical microwave signal detected by an X-band waveguide/detector combination (upper curve) and the ionizing laser (lower curve). The inset shows the calibrated power of the signal as a function of the square of dc bias voltage. The fit line has a slope of 100 mW/kV^2.

with a 6 to 1 intensity ratio. The signal had a duration less than 5 ns, the limit of time resolution of our oscilloscope. For microwave pulses between 6 and 26 GHz containing 12 half-cycles, the pulse width is expected to vary from 1 to 0.28 ns. The inset of Fig. 3 shows the converted power of the signal (measured by the calibrated microwave diode) as a function of the square of the dc bias voltage [see Eq. (2)] for a given set of parameters. Although dc biases as high as 1 kV could be applied to the structure, the diode detector was essentially saturated above 500 V bias. A linear relation was obtained with a slope of 100 mW/kV^2. However, the actual power generated in the structure is much higher because of the following two mechanisms: (1) There is a large impedance mismatch at the output of the structure. A cold test based on injecting a microwave signal (from 6 to 18 GHz) from outside the structure showed attenuation by 30–40 dB. (2) The detector has a response time which is longer (by about 1 order of magnitude) than the duration of the incoming microwave pulse. This also reduces the apparent signal intensity. The power scaling law given by Eq. (2) is about 250 W/kV^2 with $A = 0.79$ cm^2 (laser spot size), $b = 1.5$ cm, and $V_g = 0.55c$. This would be consistent with the data if the radiation were attenuated by a factor of 34 dB. We comment that, although the signal reaching the detector was only a small fraction of the power generated in the device, it was nevertheless sufficient to nearly saturate the microwave diode.

Figure 4 shows the amplitude of the detected signals measured with four different waveguide/detector combinations as a function of azulene pressure (= total pressure minus background pressure). The amplitudes of signals in this figure were normalized to the maximum signal obtained in the same bands. As the azulene pressure is increased, higher microwave frequencies should be achieved since the plasma density behind the ionization front is directly proportional to the azulene pressure in the absence of significant laser pump depletion. As shown in the figure, the signal appeared on successively higher bands when the pressure was increased. This shows a clear dependence of the onset frequency with pressure. However, the cut-off waveguide technique does not provide spectral information. Since the detectors are sensitive to frequencies above their cutoff, at higher pressures the signal appears on several bands at once. The dip that occurs between 1.5 and 4 mTorr is thought to be due to the transmission characteristics of this periodic structure (i.e., a band gap) and output coupler. We also converted the azulene pressure to the corresponding plasma density based on a previous experiment done at UCLA with the same laser and working gas [4]. The conversion factor was 9×10^{11} cm^{-3}/mT of azulene. However, in the present experiment, the laser power was only 75% of that used in the previous experiment. We expect the conversion factor to be 5.1×10^{11} cm^{-3}/mT of azulene because the ionization rate is proportional to the square of laser power for the two-photon ionization process here. Using this estimated conversion rate, we plot the frequencies of the minimum onset (i.e., the lowest nonzero points of the three curves in Fig. 4) vs plasma density in Fig. 5. The solid line represents the theoretically predicted line given in Eq. (1). For azulene pressures greater than 3 mTorr, the laser pulses were depleted because of the absorption of photons by azulene. As a result, the conversion factor is less than 5.1×10^{11} cm^{-3}/mT at pressures above 3 mT, and the plasma density is not constant along the structure. The data point corresponding to the onset of the 21.07 GHz signal is expected to drop below the theoretical line, since the plasma density is overestimated at this pressure value. Otherwise, the data (i.e., the onset density corresponding to a given cutoff frequency) are in excellent agreement with the theory.

Equation (1) indicates that the output frequency can also be tuned by adjusting the plate spacing. Although our design did not include this mechanical function, we have tested the situation with all top plates biased at the same voltage and bottom plates grounded. In this case,

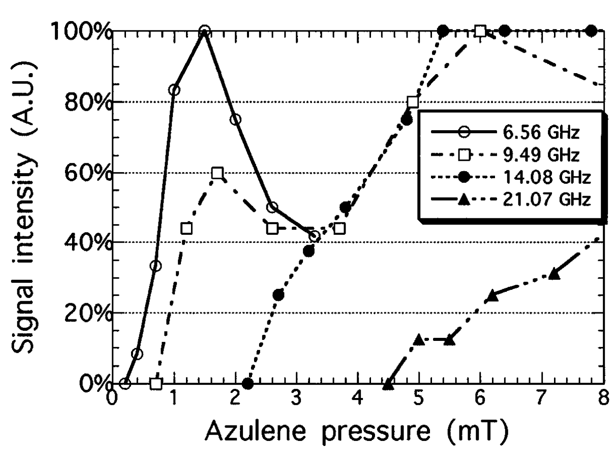

FIG. 4. Signals on the cutoff frequency $f_c = 6.56$ GHz, $f_c = 9.49$ GHz, $f_c = 14.08$ GHz, and $f_c = 21.07$ GHz waveguides versus azulene pressure.

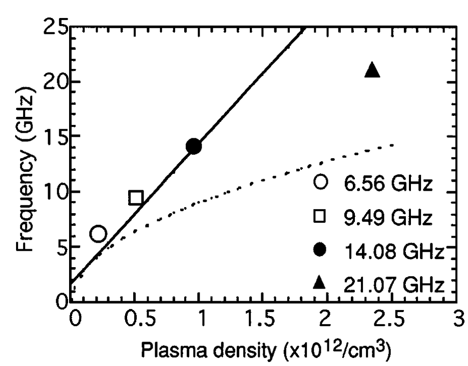

FIG. 5. Output frequency versus plasma density. The solid line is the theoretical prediction given by Eq. (1). The dotted curve is the plasma frequency $\omega = \omega_p$.

a single capacitor ($d = 56$ cm) is formed, and a half-cycle output pulse would be predicted. We observed the microwave signal to appear typically on a detector one band higher compared to the alternately biased case at the same azulene pressure. This result is consistent with the wideband frequency spectrum of a short half-cycle pulse.

We have verified the physical mechanism of up-shifting an electromagnetic wave from zero frequency to a tunable value using an ionization front. In this experiment the highest frequency detected was tuned by a factor of 3 (6–21 GHz) by varying the gas pressure. The mechanism naturally produced ultrashort pulses of microwave radiation (detection limited pulses less than 5 ns). The relative power of the signal was measured and found to scale with the square of the dc bias voltage. The results support the potential to develop high-power tunable sources of microwave to infrared radiation based on ionization fronts moving through a static field. Further work may exploit unique features of this mechanism, including the possibility of controlling the detailed output of the wave form (such as chirping and encoding) as well as its duration by individually controlling the plates' bias and separation.

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