Demonstration of the Frequency Upshifting of Microwave Radiation by Rapid Plasma Creation


Abstract—A new technique for frequency-upshifting electromagnetic radiation is demonstrated. By ionizing azulene vapor contained in a resonant cavity using a laser pulse, the frequency of the incident RF wave at 33.3 GHz is upshifted by 5% with greater than 10% efficiency. Maximum frequency upshift of 2.3 times the source frequency is observed. There are two mechanisms thought to be operative in producing the observed frequency upshift: The time-dependent dielectric constant due to increasing plasma density, and rapid "Q-switching" of the cavity. This technique has the potential of being able to generate tunable and chirped radiation over a very broad (\(\Delta f/f \approx 1\)) frequency range.

I. INTRODUCTION

THERE IS a tremendous amount of current interest in extending the capabilities of existing coherent light sources. For instance, supercontinua generated by intense ultrashort laser pulses provide broadband coherent radiation from infrared to ultraviolet [1]. Free-electron devices [2] can in principle generate continuously tunable radiation from microwaves to ultraviolet. In reality, any one such device is tunable over a limited frequency range and is very expensive. In the microwave regime, no single source can presently cover a broad frequency range \(\Delta f/f \gg 1\). In this paper we demonstrate experimentally a technique which can generate frequency-upshifted electromagnetic radiation which is particularly suited to the generation of tunable microwave radiation over a very broad frequency range.

The mechanism behind this method of upshifting the frequency of an electromagnetic (EM) wave can be explained as follows [3]: When electromagnetic radiation impinges upon a medium whose dielectric properties do not vary in time but do vary in space, then the radiation’s frequency remains constant while the wavenumber changes. On the other hand, if the dielectric properties vary in time rather than in space, the frequency will change but the wavenumber will remain constant. This is because frequency and time and similarly wavenumber and space are Fourier conjugate variables. Imagine that the source EM wave \((\omega, k)\) is propagating through a medium that is suddenly uniformly ionized. The wavenumber of this source wave \(k\) is fixed by the initial condition, but the frequency of the wave can change to \(\sqrt{\omega^2 + \omega_p^2}\), where \(\omega_p\) is the plasma angular frequency. If the plasma density is continuously but rapidly raised in time, it is clearly possible to obtain chirped radiation. Also, if the plasma frequency is larger than the source frequency, a significant amount of power can be converted to waves with a frequency \(\gtrsim \omega_p\). The theory of frequency-upshifting EM waves using a plasma goes considerably back in time [3], but this is the first time, we believe, that the phenomenon has been explored experimentally.

In this paper we describe an experiment in which 33.3-GHz source contained in a cylindrical waveguide resonator (TE01 mode) is shifted in frequency up to 77 GHz by the laser ionization of azulene vapor. There are two mechanisms thought to be operative in producing the observed frequency spectrum. First, as the laser ionizes the vapor producing a very low density plasma, the Q of the cavity is suddenly "switched," producing a broadband "Lorentzian"-like spectrum with a maximum measured frequency upshift of 2.3 times the source frequency. Secondly, as the plasma density inside the cavity builds up due to continuing laser ionization, the frequency of the source wave is shifted as described above.

This method is in some ways analogous to frequency chirping and/or broadening of an intense laser pulse by self-phase modulation [4] whereby the frequency of the incident laser light can be changed by the intensity-dependent refractive index of the medium. Such a medium may be a nonlinear dielectric or a self-breakdown plasma [5] with a time-dependent density (and therefore a time-dependent refractive index). The crucial difference in the present method is that the dielectric constant of the medium is externally varied in time, and not self-varied by the source EM wave.
II. EXPERIMENT

In an experimental situation it is impossible to instantaneously and uniformly ionize the volume $V$ of the medium. On the other hand, when using microwave radiation as the source wave already trapped inside a resonant cavity, it is possible to quasi-uniformly ionize this volume over tens of cycles of the source wave using a high-frequency ionizing laser. Although the dispersion relation for an electromagnetic wave in a wave guide $\omega^2 = \omega_0^2 + k^2 c^2$ is somewhat different than that for a plane wave in free space, the argument given previously for upshifting the frequency by rapidly creating a plasma still holds. Since the source radiation is already in the waveguide, its wavenumber is fixed by the above dispersion relation. Now, if we uniformly ionize the medium inside the waveguide and create a plasma, the frequency changes to $\omega^2 = \omega_0^2 + k^2 c^2 + \omega_p^2(t) = \omega(t)$, where $\omega_p(t)$ denotes a time-varying plasma frequency. In the case of uniform ionization, the wavenumber will not change. On the other hand, any new radiation at the source frequency entering $V$ from the outside will see both space and time-dependent changes in the dielectric properties of the medium, and both its frequency and wavenumber will be affected. Assume for the moment that at time $t = 0$ the waveguide is filled with microwaves the source frequency $\omega_0$, and after this time the cavity is decoupled from the source. Now if an ionizing laser is fired through the waveguide, then, aside from the initial one transit time of the laser radiation through the cavity, the plasma density builds up quasi-uniformly inside the cavity. The waveguide tends to fix the wavenumber of the radiation as it is being upshifted. We have carried out two-dimensional self-consistent particle simulations using the code WAVE-2D to verify the above described scenario [6]. We find that the source frequency indeed upshifts close to $\sqrt{\omega_0^2 + \omega_p^2}$. The problem with slow ionization in free space, of course, is that the source wave continues to leak out of the volume being ionized at approximately the speed of light, unless plasma densities on the order of the critical density for the source wave can be created in a time shorter than the transit time across the length $l$ of $V$. This leakage of the source radiation before a significant amount of plasma is created implies that the conversion efficiency of the device would be low. To get around the problem, we chose to confine the source wave in a waveguide resonator operating quite close to its cut-off frequency. This has two advantages: First, the group velocity of the wave is now much less than the speed of light (0.3$c$, in fact). This allows us to ionize the medium more slowly. Secondly the use of a resonant cavity allows one to build up the source radiation in the waveguide using a relatively modest power source.

The schematic of the experimental setup is shown in Fig. 1. The cylindrical resonant cavity operated on the $TE_{01}$ mode at the nominal RF source frequency of 33.3 GHz. The thickness of the quartz windows was chosen to be $5\lambda/4$ to obtain high reflectivity for the resonant frequency and thereby a reasonably high $Q$ for the cavity. The cutoff frequency $f_c$ for the $TE_{01}$ mode was 31.7 GHz, whereas for the lower order modes $f_c (TE_{11}) = 14.77$ GHz and $f_c (TM_{01}) = 19.3$ GHz. The cavity length was 13 wavelengths; the RF wavelength in the waveguide being 2.33 cm. The cavity $Q$ at the designed resonant frequency was measured to be around 1650. The cavity $Q$ fell to around 600 within $\pm 2$ GHz of the designed operating frequency.

The cavity did operate on the $TE_{01}$ mode was confirmed two ways. First, plasma emission from microwave-induced self-breakdown in the cavity was imaged. This showed the light emission coming from an annular region where the circular electric field $E_\phi$ had the maximum value. Secondly the antenna pattern of radiation emanating from the quartz window was measured. This showed the expected "butterfly pattern" and polarization dependence of the $TE_{01}$ mode. The operating frequency was chosen such that the group velocity of the source wave was 0.3$c$ and yet the attenuation constant due to resistive losses was relatively small. The main energy loss mechanism for the source wave was thus window leakage. In this sense, the resonant cavity resembled more closely an optical resonator than a microwave resonator.

The ionizing laser operated at the fourth harmonic (0.266 $\mu$m) of Nd : YAG and contained 40 mJ in an 8-ns (FWHM, full width at half maximum) pulse. The residual second harmonic and the fundamental radiation at 0.53 and 1.06 $\mu$m, respectively, were filtered to less than 4 mJ. The ionizing gas was azulene ($C_{10}H_{8}$) vapor. The vapor pressure was controlled by varying the temperature of the waveguide and azulene reservoir between room temperature and 50°C. Most of the measurements reported here were carried out at 40°C where the azulene vapor pressure was roughly 40 mT. Azulene was chosen because it has a very large absorption cross section for the 0.266-$\mu$m laser light.

The output radiation was analyzed using a selection of calibrated detectors with different rectangular cut-off waveguides. The cut-off waveguides were all 15-cm long and had $f_c (TE_{01})$ of 34.4, 40, 50, and 77 GHz. In the first three cases, the detector was an HP R 442 crystal detector. For $f_c (TE_{01})$ of 77 GHz we used a Baytron IN 5A detector. Even at the lowest cut-off frequency of 34.4 GHz, the cut-off waveguide–detector combination had an
attenuation of greater than 70 dB for the source wave. At various times the detectors were placed some distance from both the laser input and output windows of the cavity in addition to being placed in one arm of the directional coupler monitoring the reflected RF power from the cavity. Frequency-upshifted radiation could indeed be measured in all three directions when the laser was fired. The results we present now, however, were all obtained by looking at radiation from the laser-output window. The following "null-tests'' were carried out to ensure that no spurious signals were observed on the detectors and interpreted as being signatures of upshifted frequencies: a) RF but no laser; b) laser but no RF; c) self-RF breakdown; d) entrance to the cutoff waveguide blocked with thin metal foil; and e) RF and laser operating at second harmonic only. None of these tests showed signals on any of the detectors.

III. RESULTS

Fig. 2 shows what happens to the transmitted source wave, and the signals recorded on the 34.4-GHz detector when the ionizing laser is fired. The laser rise time (10-90\%) is approximately 8 ns, but 10 ns before the peak of the laser-pulse transmission of the source wave abruptly begins to decrease, falling to almost zero within 2 ns. At the same time, the source reflectivity increases to 100\%. Concurrent with the decrease in the source wave transmission from the cavity, the higher frequency detector at 34.4 GHz records a signal which typically has 1-ns rise time and exponential fall time which depends on laser intensity and fill pressure of the ionizing gas. Typically, the FWHM of the signal is about 5 ns. Although the signals on the 34.4- and 40-GHz detectors start at the same point in time to within 500 ps, the 40-GHz signal on most occasions was found to peak 2 ns later. This is shown in Fig. 3. This is considered to be preliminary evidence that the signal may be chirped. On the other hand, the signals on the 50-GHz and 77-GHz detectors not only started at the same point in time as those on the lower frequency detectors at 34.4 and 40 GHz, but they typically had resolution-limited pulsewidths of less than 1 ns; i.e., the signals peaked before the 34.4- and 40-GHz signals. This suggests that there are probably two mechanisms operative in producing the observed spectra. The first mechanism contributes to all the observed frequencies (since all the frequencies begin at the same time), and the second contributes to frequencies up to 40 GHz (since 34.4 GHz peaks later than the 50 or 77 GHz, and the 40-GHz signal peaks at a time later than the 34.4 GHz).

We can identify the first mechanism as nothing more than a rapid "Q-switching" of the cavity. One way this can happen is if the source frequency $\omega_s$ itself is changed as a low-density plasma is formed due to laser ionization. This will have several effects on the radiated wave. First, the cavity electric field will be reduced by a factor of $\omega_{\text{upshift}}/\omega_s$. Secondly, the higher frequency radiation is closer to cutoff, resulting in a slower group velocity and therefore a further drop in the radiated power from the end of the waveguide. Thirdly, through ionization nonuniformities the new radiation can couple to other modes, spreading the radiated power into a larger solid angle (as evidenced by Fig. 4). Finally, the damping of the wave in the cavity will be enhanced due to its being closer to
temporal cutoff (from 10 kW to a few hundred watts) and through both collisional (electron-neutral and electron-ion) and resonant molecular effects. Thus the power measured on an external detector can exhibit a rapid change and through both collisional (electron-neutral and electron-ion) and resonant molecular effects. Thus the power measured on an external detector can exhibit a rapid change and through both collisional (electron-neutral and electron-ion) and resonant molecular effects. Thus the power measured on an external detector can exhibit a rapid change and through both collisional (electron-neutral and electron-ion) and resonant molecular effects. Thus the power measured on an external detector can exhibit a rapid.

The second mechanism is frequency shift due to increasing plasma density because of continuing laser ionization. This time-dependent plasma frequency \( \omega_p(t) \) implies that the dielectric constant decreases in time according to \( \varepsilon(t) = (1 - \omega_p(t)^2/\omega_0^2)^{1/2} \), and consequently the source frequency increases.

Fig. 4 shows the angular distributions of the source and the 40 GHz radiation. Notice that the source radiation shows a distinct pattern of the resonant TEM01 mode, whereas the upshifted radiation is apparently unpolarized and has an extremely broad angular distribution. This is what we expect since the high-frequency radiation is now in an overmoded waveguide and many modes can simultaneously be excited.

Finally, we plot in Fig. 5 the peak power conversion efficiency \( P_{\text{upshift}}/P_{\text{incident}} \) versus the relative frequency upshift \( f_{\text{upshift}}/f_{\text{incident}} \) exiting the laser exit window. It should be remembered that the frequency-upshifted radiation typically has a few nanoseconds duration. It can be seen that the peak power conversion efficiency on the lowest frequency detectors is about 17%, falling to about 10^{-5} at 77 GHz. The estimated error in deconvolving the data is less than a factor of 2. Almost as much frequency-upshifted power can be extracted in the reflected direction through the rectangular feed waveguide. The maximum frequency upshift observed was greater than a factor of 2.3 times the incident frequency.

**IV. Discussion**

We can infer the ionization history of the plasma from the frequency-upshift measurements and measurements of the total energy absorption of the laser pulse. For instance, neglecting any ionization nonuniformity due to the laser transit time of 1 ns through the cavity, a frequency shift of 1.5 GHz corresponds to a quasi-uniform plasma density of \( -1.3 \times 10^{12} \text{ cm}^{-3} \). From the relative timing of the laser pulse and the onset of this frequency shifted signal, we know that such a low density plasma is created at the beginning of the laser pulse. The actual amount of energy necessary to volume ionize the azulene to \( 1.3 \times 10^{12} \text{ cm}^{-3} \) is less than 50 \( \mu \text{J} \). The fractional ionization at this point is about 0.1%. Absorption measurements indicate that approximately half the laser energy entering the cavity is absorbed by the azulene vapor. Assuming that all the energy goes in the ionization process (\( \sim 10 \text{ mJ} \)) at that point, the upper bound on the plasma density at the peak of the pulse must be \( \leq 1 \times 10^{14} \text{ cm}^{-3} \).

In the absence of damping we would therefore expect to see a chirped frequency output starting at the source frequency and ending up with a frequency of \( \sim 90 \text{ GHz} \) (corresponding to \( n_e \sim 10^{15} \text{ cm}^{-3} \)). Furthermore, once the plasma density approaches the critical density for the source wave, the group velocity begins to slow down. The radiation therefore remains confined inside the cavity for a longer time. Thus we might expect a reasonable efficiency even at higher frequencies. However, in the experiment, we did not see any evidence of chirping beyond 40 GHz, implying either that the peak density did not increase beyond \( 6 \times 10^{15} \text{ cm}^{-3} \) (corresponding to 40 GHz) or that the remaining radiation inside the cavity was strongly...
damped. There are three candidates for such strong damping: Electron-neutral collisions, Coulomb collisions, and coupling to vibrational–rotational modes of the azulene molecules. We have theoretically analyzed the experiment by means of a one-dimensional model which includes the finite ionization rate and competing damping in the plasma [6]. Our calculations indicate that the former two effects, although significant, probably cannot account for the implied strong damping of the radiation inside the cavity. On the other hand, resonant coupling to the vibrational–rotational modes of the azulene molecule remains a strong possibility. Further work is necessary to resolve this important issue. In future experiments it would be desirable to use either a more intense laser pulse to produce more rapid ionization or a medium which can be more readily ionized than azulene. If fractional ionization approaching unity could be produced, we believe that this technique can be used to generate continuously tunable radiation of up to 100’s of GHz, and perhaps to even higher frequencies.

In conclusion, we have demonstrated that the frequency of an electromagnetic source wave can be upshifted by rapidly ionizing the medium through which the source wave is propagating. The frequency of 33.3-GHz microwave radiation was upshifted by 1.5 GHz with good power conversion efficiency. Maximum frequency upshift of 2.3 times the source frequency was observed in these experiments.

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