Frequency Up-Conversion of Microwave Pulse in a Rapidly Growing Plasma

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Two crossed microwave pulses are used to generate plasma in their intersection region inside a chamber. It is shown that the frequency of each output pulse is up-shifted. The percentage of frequency shift is consistent with the theory of Wilks, Dawson, and Mori. Besides frequency shift and some attenuation, the similarity between the spectral distributions of the output and input pulses indicates that there is very little distortion to the pulse shape.

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Recently, Wilks, Dawson, and Mori[1] have studied an initial-value problem concerning the propagation of an electromagnetic wave through a gas which is ionized in a very short time interval on the order of the period of this wave. The results of their 1D and 2D particle-in-cell computer simulations show that the frequency of the wave is up shifted and confirm their linear theory for the ideal case of instantaneous plasma creation. The physical mechanism of this frequency up-conversion phenomenon becomes quite clear by noting that the wavelength of the wave does not change after the ionization of the gas since the wave does not encounter any spatial variation in the medium; however, the sudden reduction of the index of refraction of the gas by converting it into a plasma forces the wave to propagate with larger phase velocity and, thus, to oscillate with higher frequency at subsequent times.

However, using a single high-power laser pulse for plasma generation and, subsequently, for its frequency up-conversion purpose was shown to be unpractical in the previous experiment by Yablonovitch.[2] His experiment showed only spectral broadening in the CO_2 laser pulse transmitting through a rapidly growing plasma. We believe that this is because plasma is preferentially generated at the boundary where input pulse and ionized medium first encounter.

In this work, we use two crossed microwave beams with parallel polarization for establishing an initial-value problem. In doing so, we can adjust the intensity of each beam so that a discharge of background gas occurs only in the intersection region of the two beams. The experiment is conducted in a chamber of a 2-ft Plexiglas cube. The carrier frequency of the 1.1-μsec microwave pulses used in the experiment is 3.27 GHz. Shown in Fig. 1(a) is the envelope of each pulse. The chamber is hence more than six wavelengths long and is long enough to shield the boundary effect from the wave over a single wave period. The microwave power is generated by a single magnetron tube (OKH1448) driven by a soft tube modulator having a repetition rate of 60 Hz. The peak output power of the tube is 1 MW. Since we are interested in an initial-value problem, we have to ionize the gas simultaneously over the chamber. However, using a single pulse can only generate a localized plasma near the chamber wall. A second pulse provided by the same magnetron tube is fed into the cube through a second S-band microwave horn placed at a right angle to the first one. With such an arrangement, the power of each pulse can be reduced to below the breakdown threshold of the gas and breakdown of gas can occur only in the central

(a)

(b)

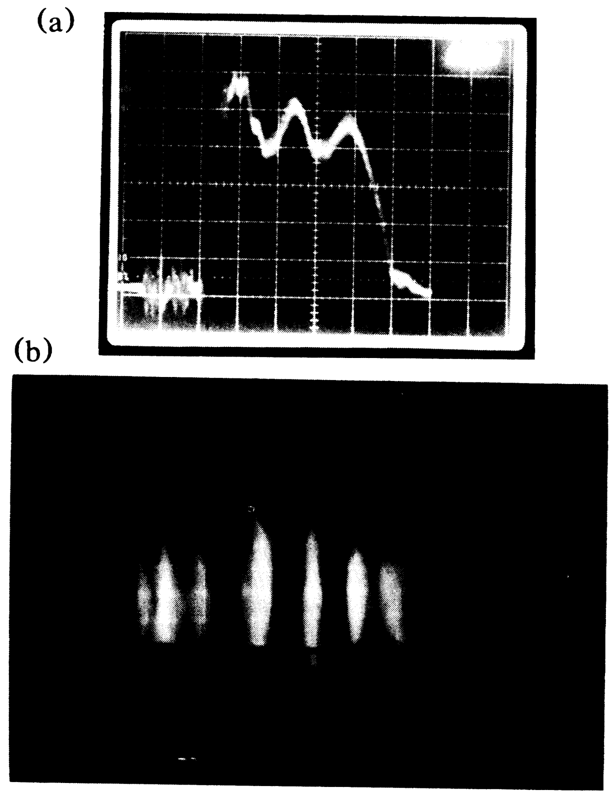

FIG. 1. (a) Envelope of a 1-μsec microwave pulse. (b) A photo of plasma layers generated by two cross pulses having parallel polarization.

region of the chamber where the two pulses intersect. The undesired tail erosion to the pulses by the generated plasma can also be minimized. The wave fields add up to form a standing-wave pattern in the intersecting region in the direction perpendicular to the bisecting line of the angle between the two intersecting pulses. Thus, parallel plasma layers with a separation $d=\lambda_0/\sqrt{2}$ can be generated, where λ_0 is the wavelength of the wave. Two phase shifters are used to extend the region covered by the plasma layers. A maximum of eight layers detected visually can be generated to cover almost the entire path of the first pulse in the chamber.[3] A photo of the plasma layers is presented in Fig. 1(b), where only seven layers are clearly shown. A block diagram of the experimental setup is shown in Fig. 2.

Although the produced plasma is not spatially uniform, it extends over several wavelengths and has a temporal growing average density along the path of the first pulse. The periodic spatial variation of plasma density may cause scattering and, hence, additional attenuation to the incident pulse. Nevertheless, it should not affect the observation on frequency up-shift phenomenon. Since our pulse length is about 300 m long, which is much longer than the length 0.6 m of the chamber, one may divide the pulse into 500 segments and each segment of the pulse experiences a frequency shift while it is inside the chamber. Therefore, the maximum frequency shift on the output pulse is just the maximum frequency shift on each segment. Consequently, only a small fraction of total density change over the pulse period can contribute to the frequency shift. In order to enhance frequency shift, one would have to increase the ionization rate. However, this cannot be done by simply increasing the pulse amplitude because gas breakdown can occur locally near the chamber wall, and the nature of initial-value problem is demolished. We find that if we mix dry air with argon gas with total pressure about 2.3 Torr, maximum frequency up-shift is achieved. This is because dry air has a high breakdown threshold which enables us to increase the pulse amplitude without causing serious tail erosion and argon is helping the initial ionization for the subsequent electron-density growth. Shown in Fig. 3 is the frequency spectra of output pulses with and without plasma generation. The corresponding input spectra were also examined. No noticeable difference between the two input spectra was observed. A 1.5-MHz frequency up-shift is clearly demonstrated in Fig. 3. It is noted that the sweep time of the spectrum analyzer is 50 sec. Thus, each recorded spectrum of Fig. 3 represents an average sampling spectrum of 3000 pulses. If the frequency shift of each pulse is not the same, the recorded spectrum should reveal a mean frequency shift as well as spectral broadening. However, no noticeable spectral broadening appeared in the recorded spectrum (curve 2 of Fig. 3), and no noticeable change in the amount of frequency up-shift over many sweeping periods can be detected either. Besides a frequency shift and an attenuation caused by the plasma generation, the similarity between the spectrum of the two pulses indicates that the distortion to the pulse shape due to the plasma generation is very small.

In the density range of interest ($\leq 10^{11}$ cm^{-3}), the dominant loss mechanism of free electrons in the dry air is through their attachment with neutral molecules. The maximum attachment rate[4] υ_a of dry air at 2.3 Torr is about 3.22×10^5 sec^{-1}. Hence, breakdown occurs only when the ionization rate υ_i is larger than the attachment rate υ_a. The relationship between υ_i and υ_a is shown[4] to be $\upsilon_i/\upsilon_a \sim (E/E_c)^{5.3}$ for a long pulse and $1.3 < E/E_c < 3.5$, where E_c is the breakdown threshold field of the dry air and can be expressed[4] as

$$E_c \triangleq 28(N_m/2.7\times10^{19})(1+\omega_0^2/\nu_c^2)^{1/2}\ \text{kV/cm}\,,$$

N_m is the number of neutrals per cubic centimeter, and

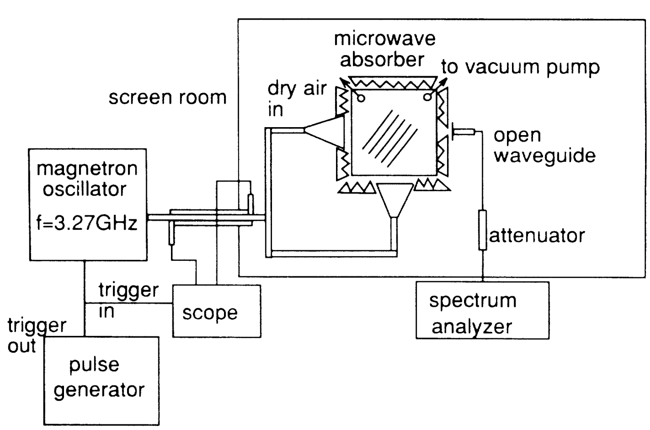

FIG. 2. Experimental configuration.

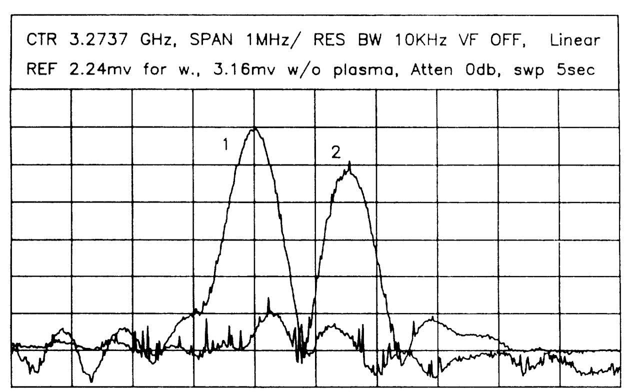

FIG. 3. Frequency spectra of two output pulses with same input. Curve 1 is the spectrum of the pulse passing through the chamber (at the pressure ~1 atm) without plasma generation and curve 2 represents the spectrum of the pulse passing through a rapidly growing plasma generated inside the chamber (at the pressure ~2.3 Torr).

ν_c is the electron-neutral collision frequency. In this experiment, $\omega_0^2/\nu_c^2 \gg 1$, thus $E_c \sim \omega_0/\nu_c$. Since ν_c is proportional to electron speed and in the present case the electron quiver speed $eE/m\omega_0$ is much larger than the electron thermal speed, then $\nu_c \sim E$ and this leads to $\nu_i \sim (E/E_c)^{5.3} \sim E^{10.6}$; a very strong dependence of the ionization frequency ν_i on E is shown. It is a disadvantageous feature for controlling the frequency shift by self-generated plasmas. On the other hand, it becomes an advantageous feature for possibly minimizing the spectral broadening on the frequency-shifted output pulse as indicated by the result shown in Fig. 3. The amount of electron-density change contributed to frequency shift of each pulse segment depends not only on the ionization frequency ν_i but also on the available time period τ during which the initial effect dominates over the boundary effect, where τ is a time-dependent function. In the beginning of the pulse, the background electron density is low and hence the boundary effect is weak. Thus, the initial effect can prevail over the boundary effect for almost the entire period of the pulse segment; i.e., $\tau_0 = l/c$, the transit time of the pulse through the chamber. τ decreases, however, as the electron density increases. The density change of plasma electrons available for the frequency shift of each pulse segment is then given by $\Delta n_e/n_0 \sim \nu_i \tau$. Since each segment of the pulse suddenly experiences half of such a fractional electron-density increase on the average, while passing through the chamber, the dispersion relation of the carrier of the pulse should also change accordingly in time from $\omega_0^2 = \omega_{p0}^2 + k_0^2 c^2$ to

$$\omega_f^2 = (\omega_{p0} + \Delta\omega_p)^2 + k_0^2 c^2 = \omega_0^2 + 2\omega_{p0}\Delta\omega_p + \Delta\omega_p^2 .$$

In the region $\Delta\omega_p \ll \omega_{p0}$, we have

$$\omega_f \approx \omega_0 (1 + 2\omega_{p0}\Delta\omega_p/\omega_0^2)^{1/2} \approx \omega_0 (1 + \omega_{p0}\Delta\omega_p/\omega_0^2) .$$

Since $\Delta\omega_p/\omega_{p0} = \frac{1}{2}\langle \Delta n_e/n_0 \rangle = \frac{3}{8}\Delta n_e/n_0$, we then have the frequency up-shift

$$\Delta f_0/f_0 = \tfrac{3}{8}(\Delta n_e/n_0)\omega_{p0}^2/\omega_0^2 \sim \nu_i \tau n_0 .$$

In general, this frequency shift is a function of time. It would be the case of a rectangular pulse and lead to a spectral broadening because each pulse segment experiences a slightly different frequency shift. However, no apparently spectral broadening is shown in the result (curve 2) presented in Fig. 3. On the other hand, the pulse envelope shown in Fig. 1(a) is not exactly a rectangular pulse either. It shows that the pulse has a decreasing amplitude (on average). It means that ν_i decreases while n_0 increases. It is verified by the Bragg scattering result. Since the generated plasma is a set of parallel layers, one can use the Bragg scattering method[3] to monitor the growth and decay of plasma electrons, where the scattering coefficient is proportional to $n_0^2(t)$. As shown in Fig. 4, the intensity of the scattering signal after emerging out of the noise level increases with a decreasing rate. In order to minimize the spectral broadening on the frequency-shifted output pulse, it requires that $\nu_i \tau n_0 \sim$const over a large portion of pulse length. Considering the portion of the pulse from its peak to the half-peak point ($\sim$0.7-μsec interval), a self-consistent set of the solution of the rate equation $dn_0/dt = \nu_i n_0$ given by $n_0 = n_1(1 + \nu_{i0}t/1.25)^{1.25}$, $\nu_i = \nu_{i0}/(1 + \nu_{i0}t/1.25)$, and $\tau = \tau_0/(1 + \nu_{i0}t/1.25)^{0.25}$, with $n_1 = 2.5 \times 10^7$ cm^{-3}, $\nu_{i0} = 2.94 \times 10^9$ sec^{-1}, and $\tau_0 = l/c \sim 2$ nsec, leads to a constant frequency shift with a value about 1.4 MHz consistent with the experimental result. Using the function $\nu_i(t)$ and the relation $\nu_i \sim E^{10.6}$, the envelope of a 0.7-μsec pulse can be reconstructed and is found to overlap closely with the original pulse envelope in the corresponding interval [Fig. 1(a) with average amplitude]. This explains why there is no apparently spectral broadening appearing in curve 2 of Fig. 3. It is noted that at the end of the pulse, the average plasma density is about the cutoff density of each input pulse, i.e., $\langle \omega_p^2 \rangle \approx \omega_0^2 = \frac{1}{2}\omega_p^2|_{\rm peak}$.

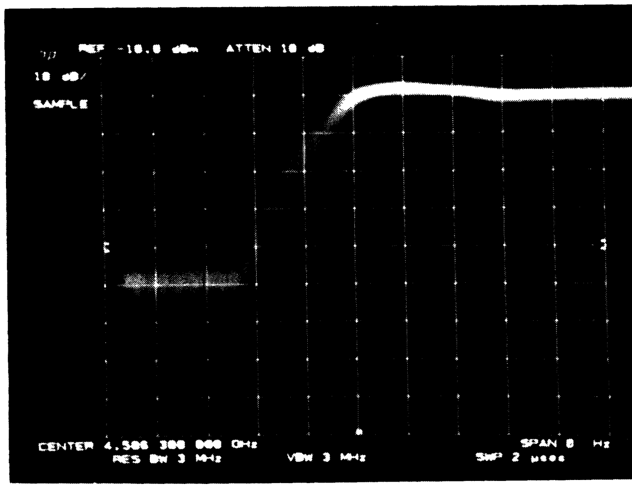

FIG. 4. The growth and decay of the intensity of Bragg scattering signal during the first 2-μsec period.

In summary, we have demonstrated experimentally that it is possible to up-shift the carrier frequency of an electromagnetic pulse by passing it through a rapidly growing plasma. Though the achieved frequency shift is small, it is mainly because the pulse length of the present experiment is much longer than the size of generated plasma. If the pulse length can be reduced to be comparable to the length of the chamber (e.g., using 2-nsec pulses), the field intensity of each pulse can be increased considerably without causing gas breakdown near the chamber wall. Thus, the ionization rate of gas in the intersecting regions of two pulses can be increased by a factor of about 500, and a frequency shift $\Delta f_0/f_0 \sim 0.26$ is expected. In order to minimize spectral broadening on output pulses, a proper shaping of the input pulses is required.

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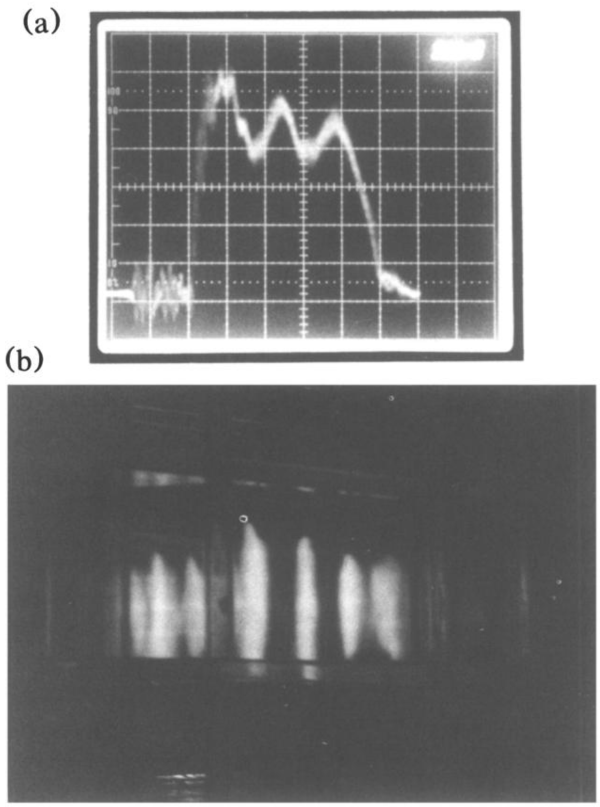

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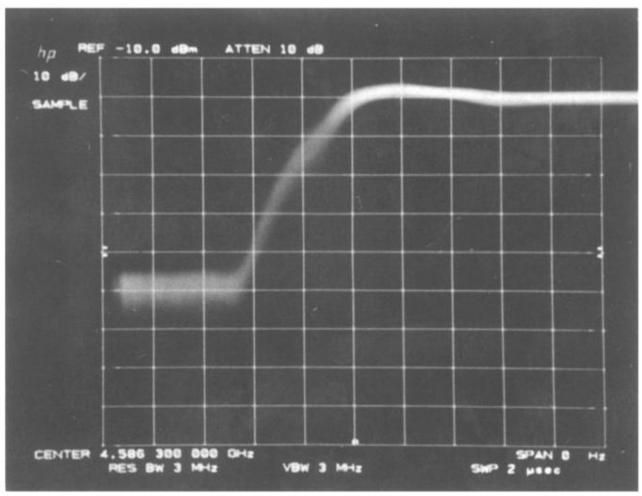

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