Excitation of high-frequency oscillations by a laser pulse

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(Submitted 30 May 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 2, 115–119 (20 July 1980)

We investigate the excitation of high-frequency electromagnetic oscillations when a laser pulse is applied to an electrode connected to a resonance circuit. There is a marked increase in the amplitude of the oscillations as the front of the laser pulse is steepened. Amplitudes of ~100 A at frequencies of ~100 MHz are obtained for current oscillations. The possibility of exciting sub-centimeter and sub-millimeter oscillations by means of picosecond laser pulses is discussed for the case when planar or volume resonances are used, and the resonant driving of laser-modulated oscillations is examined. Possible applications of these effects are mentioned.

PACS numbers: 42.60. – v, 41.10.Hv, 84.90. + a

In recent years there has been active research on the generation of powerful quasi-static currents and magnetic fields in optical[1-3] and microwave[4] plasmas by the action of radiation on electrodes.

In this letter we report the study of a new effect—the excitation of intense high-frequency electromagnetic oscillations by the action of laser pulses on an electrode in a resonance circuit.

The experimental layout is shown in Fig. 1. Pulsed radiation with a variable pulse shape from a modulated neodymium laser (1) at powers up to 300 MW was focused by a lens of focal length 8.5 cm into a vacuum chamber (2) and onto a copper target (3) surrounded by a grounded copper cylinder (4) of radius 1 cm. The target was connected to a circuit whose resonance frequency ν_0 depended on the inductance and capacitance of the circuit. The inductance L was about 10^2 nH and the capacitance C was varied between 20 and 10^4 pF, corresponding to a resonance frequency ν_0 between 150 and 4 MHz. The voltage U_C on the capacitor was applied by cable to an oscilloscope through a resistance $R = 10$ kΩ. For additional monitoring, an small inductionless resistance $r = 0.2$ Ω was placed in the circuit either instead of the capacitor or in series with it; the voltage U_r across this resistor characterized the current in the circuit.

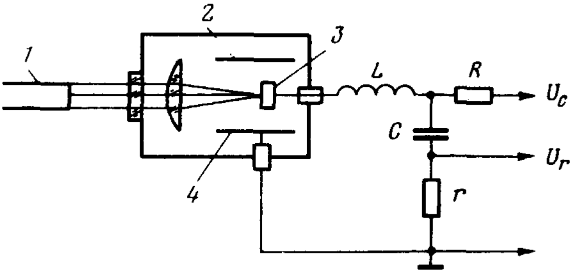

FIG. 1. Diagram of apparatus: 1—laser, 2—vacuum chamber, 3—copper target, 4—grounded cylinder.

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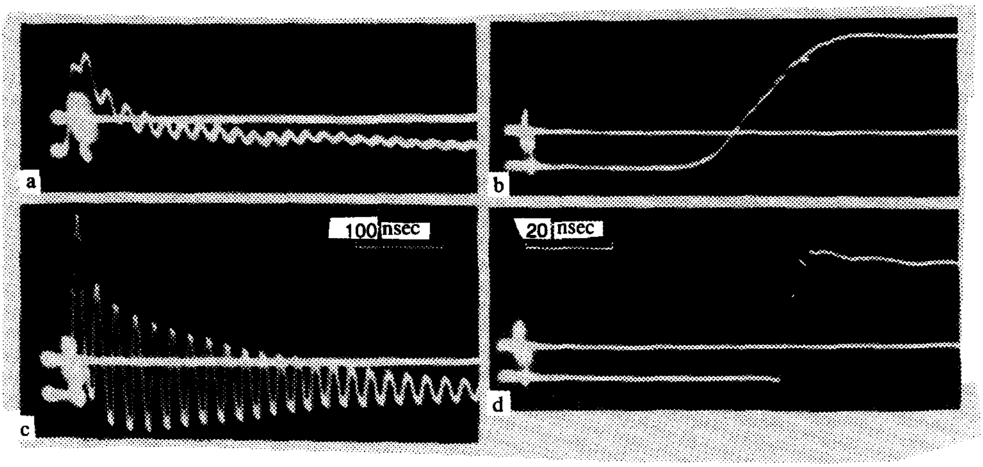

FIG. 2. Oscillograms of oscillations and pulses in the laser illumination of a target: a—oscillation of U_C in the resonance circuit ($C = 100$ pF, $\nu_0 = 45$ MHz) for unclipped laser pulse. It is seen that the amplitude of the oscillations is small compared to that of the rise in the potential; b—oscillations of U_C in the same resonance circuit under the action of a pulse with a chopped front. A marked increase in the amplitude of the oscillations is observed; c—current pulse in the circuit without the capacitor for the unclipped laser pulse; d—the same for a pulse with a chopped front. The steepening of the current front can be seen.

The pressure in the chamber was 10^{-2} torr, the value at which the laser-emission current was maximum. (This maximum was first observed by the authors,[3] and its existence was later confirmed by other investigators.[5,6]

We determined the dependence of the efficiency of generation of oscillations in the circuit on the size and shape of the laser pulse.

Figure 2a shows an oscillogram of the oscillations of the capacitor voltage under the action of a laser pulse with an almost Gaussian shape and a half-width of 40 nsec. When a laser pulse with a steep front was used, the amplitude of the oscillations grew many times larger (Fig. 2b). Pulses of this kind were obtained by passing the original pulses through a metallicized lavsan (Dacron) film, which shortened the front to several nanoseconds. Shortening the front of the laser pulse caused the current front to be sharpened in the case when there was no capacitor in the circuit as well (Figs. 2c and 2d).

It was observed that the use of a steep laser pulse on a target connected to the resonance circuit increased the amplitude of the oscillations by more than an order of magnitude (the increase was particularly large for small capacitances $C \approx 100$ pF), with the oscillations of both the voltage and the current being of alternating sign. This showed that current of the opposite polarity also flows in the interelectrode gap (arcing back or capacitive switching in the interelectrode gap containing the laser plasma).

The amplitudes of the oscillations were commensurate with the voltages used, a characteristic feature of pulsed excitation of a circuit. In fact, the amplitude A_0 of the oscillations during excitation of a circuit with resonance frequency ν_0 in the presence of an emf is governed by the equation

$$\ddot{U}_C + \omega_0^2 U_C = E(t)\omega_0^2 .$$

For example, if $E(t) = E_0(1 - e^{-t/\tau_f})$ the amplitude of the oscillations is $A_0 \approx E_0/\sqrt{1+(\omega_0\tau_f)^2}$ for a steady voltage of $U_\infty = E_0$, i.e., $A_0/U_\infty \approx 1/\sqrt{1+(\omega_0\tau_f)^2}$. It is seen that for $\omega_0\tau_f \gg 1$ the amplitude of the oscillations is small, but it increases as the rise time τ_f decreases. For an unclipped pulse, $\omega\tau_f \gg 1$ if C is not too large, and the shortening of the front is important. For practically all values of the C the rise of the pulse could be considered instantaneous in the case when the pulse was chopped. Therefore, one can simply estimate the effect of the duration of the emf on the excitation of oscillations by setting $E(t) \approx E_0 e^{-t/T}$ for $t > 0$, where T is the duration of the emf (of the order of hundreds of nanoseconds). Solving for the oscillations, we obtain

$$U_C \approx E_0 \frac{(\omega_0 T)^2}{1+(\omega_0 T)^2}\left\{\frac{\sqrt{1+(\omega_0 T)^2}}{\omega_0 T}\sin(\omega_0 t + \phi) + e^{-t/T}\right\},$$

where $\phi = \arctan(\omega_0 T)$, i.e. for $\omega_0 T \gg 1$ this gives $U_C \approx E_0\{\cos\omega_0 t + e^{-t/T}\}$, while for $\omega t \ll 1$ (low frequencies at large capacitances) one has $U_C \approx E_0(\omega_0 T)\{\sin\omega t + e^{-t/T}\}$, i.e., the amplitude of the oscillations decreases as the frequency of the oscillations increases. This explains why the amplitude of the oscillations was maximum for small capacitances.

We observed amplitudes of hundreds of volts and currents of tens of amperes for oscillations at frequencies up to 100 MHz. Figure 3 gives the amplitudes of the voltage and current and the frequency and damping time τ of the oscillations as functions of the capacitance C. Because the emf fell off much more smoothly than it rose, the fall-

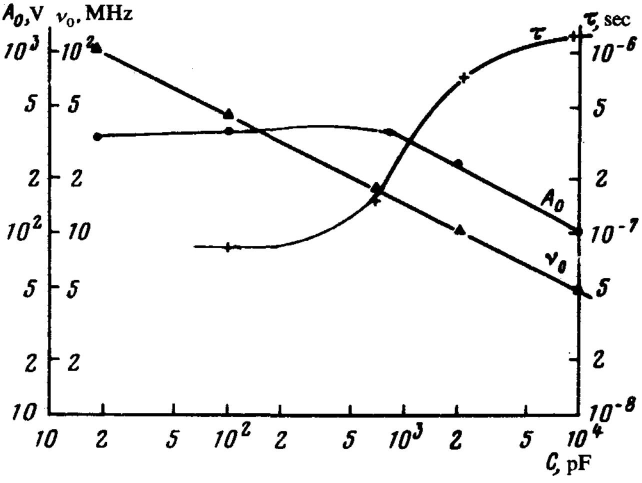

FIG. 3. Experimental behavior of the amplitude A_0, frequency ν_0, and damping time τ as functions of the capacitance C.

off did not excite oscillations, and the damping of the oscillations was governed mainly by the damping in the circuit, i.e., by the ratio $L/R_{\rm tot}$, where $R_{\rm tot} = r + R_{\rm plasma}$. Using the damping times, which were of the order of tenths of microseconds, we were able to estimate the resistance of the plasma as being of the order of tenths of ohms. The damping time characteristically increased as C was increased.

In a number of cases we observed (in measuring U_r) asymmetric current oscillations, for which the amplitudes and durations of the half-periods of the backward oscillations differed from those of the forward oscillations by a factor of several times (the back current was smaller, but lasted longer); this was evidently due to the rectifying properties of a plasma gap.

We observed oscillations at a frequency greater than 150 MHz with no capacitance in the circuit other than its intrinsic capacitance.

Going to steeper fronts or shorter pulses will enable one to excite oscillations in the region of the eigenfrequencies of striplines and resonators, i.e. to the uhf and millimeter range (recall that the rise time of the picosecond laser pulses, ~1–10 psec, corresponds to even the sub-millimeter range).

Steepening the front of the laser pulse can increase the efficiency of excitation not only through the percussive nature of the excitation, but also through the possible increase of the temperature and emf of the laser plasma.

It is possible to drive the oscillations by resonantly modulated laser radiation or by a sequence of pulses creating emf pulses that are synchronous with the driven oscillations, leading to an increase in the efficiency of conversion of beam energy into current. In multiple-pulse operation we obtained a marked enhancement of the still undamped laser-emission current pulses created by the previous laser pulses for intervals between pulses of 50 to 100 nsec; this demonstrates the possibility of multiple and resonant driving of oscillations.

It is possible that the high microwave power-to-current conversion efficiency that was recently observed[4] was due to just such hidden resonances of the plasma layers and electrodes, and that it could be increased still further by deliberate selection of the resonances.

There are other possible uses for this type of excitation in producing antenna signals.[7]

The amplification of laser-emission starting currents by an external electric field under the action of a laser beam (sectioned or incident on a channeled target[8]) may permit progress to higher frequencies and higher powers.

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