Second-harmonic generation in a graded-density plasma containing a colloidal net

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An experimental scheme is proposed to enhance the second-harmonic generation. It consists of a cylindrical waveguide filled with a graded-density plasma and containing a colloidal net whose atoms form a two-level system. An intense laser pulse incident on the waveguide propagates inside and "halts" in the colloidal net where it excites the atoms by the two-photon absorption mechanism. The subsequent stimulated emission yields a radiation at double the initial frequency.

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I. INTRODUCTION

The generation of a second-harmonic radiation is useful as a technique to obtain a higher-frequency radiation from a lower-frequency radiation[1]. It can be achieved in various ways, e.g., by allowing a laser beam to pass through a nonlinear crystal[2] or anisotropic plasma[3]. The yield of the second-harmonic radiation in such conventional methods is, however, poor. This paper proposes a novel scheme whereby the frequency of a laser pulse can be doubled with considerable efficiency.

The above-mentioned scheme consists of a cylindrical waveguide filled with a graded-density plasma[4] and containing a colloidal net[5] before the plane, where the plasma frequency equals the laser frequency. The colloidal atoms are such that they can be excited by the two-photon absorption mechanism[6] by the laser pulse which has halted in the colloidal net. The subsequent stimulated emission[7] from the net yields a radiation at double the initial frequency.

II. EXPERIMENTAL SCHEME

As shown in Fig. 1, the experimental scheme consists of (i) a cylindrical plasma waveguide of length L, (ii) a colloidal net immersed in the plasma between $z = L/3 - l$ and $z = L/3$, where z denotes the axial distance, (iii) a laser pulse of appropriate spatio-temporal distribution, and (iv) a detector near the exit of the waveguide.

As shown in Fig. 2, the electron number density N of the plasma varies with z in the form

$$N = \begin{cases} 0 & \text{for} \quad 0 > z > L, \\ C(z/L)^2 & \text{for} \quad 0 \leqslant z \leqslant L/2, \\ C(1 - z/L)^2 & \text{for} \quad L/2 \leqslant z \leqslant L. \end{cases} \tag{1}$$

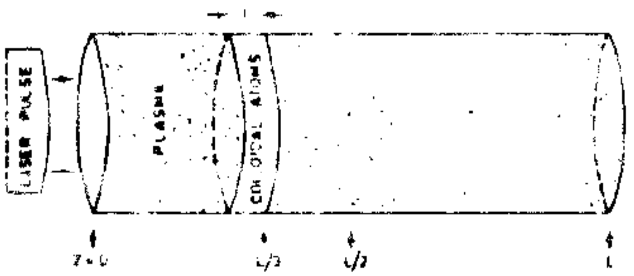

FIG. 1. Schematic diagram of the proposed experimental scheme.

The coefficient C appearing here is defined as

$$C = 9\omega^2 m/4\pi e^2, \tag{2}$$

where ω is the laser frequency. The parabolic cusp-type density distribution mentioned here may be obtained by some pressure-gauging technique.[4]

The plasma frequency ω_p is related to N by relation[4]

$$\omega_p^2 = 4\pi N e^2/m. \tag{3}$$

Hence Eq. (1) implies that ω_p varies with z in the form

$$\omega_p = \begin{cases} 0 & \text{for} \quad 0 > z > L, \\ 3\omega(z/L) & \text{for} \quad 0 \leqslant z \leqslant L/2, \\ 3\omega(1 - z/L) & \text{for} \quad L/2 \leqslant z \leqslant L. \end{cases} \tag{4}$$

Figure 3 depicts the variation of ω_p with z.

The forementioned net[5] is formed by introducing some atoms in the plasma, in the region between $z = L/3 - l$ and $z = L/3$; the thickness l of the net is much smaller than the length L of the waveguide. The structure of the atoms is such that

$$E_1 - E_0 = 2\hbar\omega < E_2 - E_1, \tag{5}$$

where E_j denotes the energy of the jth energy level. Thus these atoms form a two-level system[7].

An intense laser pulse of short duration τ_p (~ 10[illegible] sec) and of frequency ω is incident normally at the entrance ($z = 0$) of the waveguide. The cross section of the laser pulse is smaller than that of the waveguide.

III. THEORETICAL ANALYSIS

It is assumed that the laser pulse is not intense enough to redistribute the plasma particles[8] or to undergo "normal"

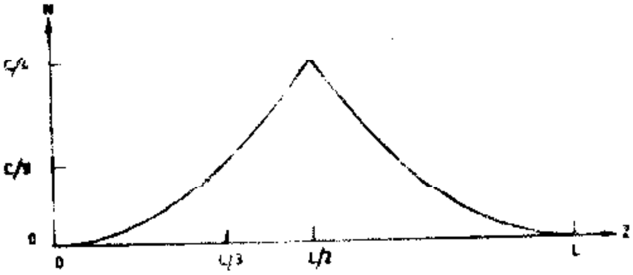

FIG. 2. Variation of the electron number density of the plasma along the waveguide.

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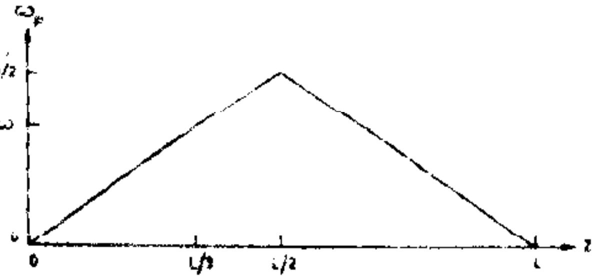

FIG. 3. Variation of the plasma frequency along the waveguide

two-photon absorption[6] inside the colloidal net. Then the nature of propagation of the laser pulse from $z = 0$ to $z = L/3$ is linear[9]. Let

$$f_{A1} = E_{A1}/E_{T0}, \tag{6}$$

$$f_{T1} = E_{T1}/E_{T0} = 1 - f_{A1}. \tag{7}$$

Here E_{T0} denotes the laser energy entered through the plane $z = 0$, E_{A1} denotes the laser energy absorbed linearly[9] during the propagation of the laser pulse from $z = 0$ to $z = L/3$, and E_{T1} denotes the laser energy reaching the plane $z = L/3$.

At $z = L/3$, the laser frequency ω equals the local plasma frequency $\omega_p(z = L/3)$. Here the laser pulse can undergo[9] resonance absorption, reflection, and tunneling. Let

$$f_{A2} = E_{A2}/E_{T1}, \tag{8}$$

$$f_{R1} = E_{R1}/E_{T1}, \tag{9}$$

$$f_{T2} = E_{T2}/E_{T1} = 1 - f_{A2} - f_{R1}. \tag{10}$$

Here[9] E_{A2} denotes the laser energy absorbed resonantly at/around the plane $z = L/3$, E_{R1} denotes the laser energy reflected from the plane $z = L/3$, and E_{T2} denotes the laser energy (at frequency ω) crossing the plane $z = L/3$.

Inside the colloidal net, the photons are retracing their path. Because of the subsequent "deceleration," the effective velocity c_b of the photons in the backward direction is much smaller than the velocity C_f of the photons in the forward direction. Therefore the photons reflected from the plane $z = L/3$ tend to "cling" to the colloidal net. This clinging leads to "induced" two-photon absorption of the laser energy by the colloidal atoms. Let

$$f_{A3} = E_{A3}/E_{R1}, \tag{11}$$

$$f_{R2} = E_{R2}/E_{R1} = 1 - f_{A3}. \tag{12}$$

Here E_{A3} denotes the laser energy absorbed in the colloidal net by the induced two-photon absorption mechanism and E_{R2} denotes the laser energy propagating towards the entrance after escaping the colloidal net.

The atoms excited by the induced two-photon absorption mechanism do not remain in the excited state. They tend to come down[7] by the mechanisms of spontaneous and stimulated emissions. Let

$$f_{E1} = E_{E1}/E_{A3}, \tag{13}$$

$$f_{E2} = E_{E2}/E_{A3}, \tag{14}$$

$$f_{A4} = E_{A4}/E_{A3} = 1 - f_{E1} - f_{E2}. \tag{15}$$

Here[7] E_{E1} is the energy emitted by the colloidal atoms by the spontaneous emission mechanism within the time duration under consideration, E_{E2} is the energy emitted by the colloidal atoms by the stimulated emission mechanism, and E_{A4} is that part of the energy which has been absorbed by the colloidal atoms by the induced two-photon absorption mechanism but has not been emitted back. The energies E_{E1} and E_{E2} are in the form of photons at frequency 2ω. The energy E_{E1} propagates randomly, whereas the energy E_{E2} propagates in the direction of the stimulating radiation, i.e., towards the exit of the waveguide.

The radiation at $z = L$ is contributed by

E_{T2}, E_{E1}, and E_{E2}. Let

$$f_{T3} = E_{T3}/E_{T2}, \tag{16}$$

$$f_{T4} = E_{T4}/E_{E1}, \tag{17}$$

$$f_{T5} = E_{T5}/E_{E2}, \tag{18}$$

$$E_{T6} = E_{T3} + E_{T4} + E_{T5} = E_{T3} + E_{T7}, \tag{19}$$

$$E_{T7} = E_{T4} + E_{T5}, \tag{20}$$

$$f_{T6} = E_{T3}/E_{T6}, \tag{21}$$

$$f_{T7} = E_{T7}/E_{T6} = 1 - f_{T6}, \tag{22}$$

$$f_{T8} = E_{T7}/E_{T0}. \tag{23}$$

Here E_{T3} is the energy of photons at frequency ω reaching $z = L$, E_{T4} is the energy of spontaneously emitted photons at frequency 2ω reaching $z = L$, and E_{T5} is the energy of stimulatedly emitted photons at frequency 2ω reaching $z = L$.

The content of 2ω frequency radiation in the outcoming radiation is determined by the ratio f_{T7} and the efficiency of conversion of the incoming (ω frequency) radiation into 2ω frequency radiation is determined by the fraction f_{T8}. The content ratio f_{T7} and the efficiency ratio f_{T8} may be expressed in terms of other "basic" ratios as follows:

$$f_{T7} = 1 - \frac{f_{T3} f_{T2}}{f_{T3} f_{T2} + (f_{T4} f_{E1} + f_{T5} f_{E2}) f_{A3} f_{R1}}, \tag{24}$$

$$f_{T8} = (f_{T4} f_{E1} + f_{T5} f_{E2}) f_{A3} f_{R1} f_{T1}. \tag{25}$$

It is easily understood that

$$f_{T3} f_{T2} \simeq 0, \tag{26}$$

$$f_{T4} f_{E1} \ll f_{T5} f_{E2}. \tag{27}$$

Consequently,

$$f_{T7} \simeq 1, \tag{28}$$

$$f_{T8} \simeq f_{T5} f_{E2} f_{A3} f_{R1} f_{T1}. \tag{29}$$

In a collisionless plasma,[8]

$$f_{T1} \simeq 1, \tag{30}$$

$$f_{T5} \simeq 1. \tag{31}$$

In view of the experimental scheme under consideration, we may assume[7] that

$$f_{R1} \sim 0.6, \tag{32}$$

$$f_{A3} \sim 0.5. \tag{33}$$

Then Eq. (29) implies

$$f_{T8} \simeq 0.3 f_{E2}. \tag{34}$$

The ratio f_{E2} depends on the temporal distribution of the laser intensity, i.e., on the pulse shape. By proper tailoring of the laser pulse, it is possible to get[7]

$$f_{F2} > 0.5 \tag{35}$$

and hence to get

$$f_{T2} > 0.15 \tag{36}$$

Equations (28) and (36) lead to the following conclusion: the experimental scheme under consideration produces almost monochromatic radiation at double the initial frequency, with an overall effeciency greater than 15%.

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