The gain coefficient of high harmonics

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High harmonics produced by laser irradiated atoms provide a source of coherent radiation in the hard-ultraviolet and soft-x-ray regime. Advancements of laser technology have made it possible to attain a large number of high-harmonic quanta per pulse ($N_s \approx 10^7$ to 10^{10}) at comparatively high gas densities (pressures between 10 and 100 Torr) [1, 2]. However, the high-harmonic *intensities* that have been reached by now are much less than necessary for many practical applications. Therefore, any method that has the potential of yielding a higher intensity is of great interest. One of these possibilities is the amplification by stimulated emission of a high-harmonic probe wave passing through the atomic medium in the presence of the pump wave.

The problem of the amplification of a probe wave in such a situation was considered for the first time in [3]. In the present work, the gain of the 15th harmonic of a Ti:sapphire laser is calculated on the basis of these previous results [3]. Two different situations are discussed, high-harmonic generation occurring (i) in an atomic jet and (ii) in a gas-filled hollow-core fiber.

We consider the amplification of a high-order harmonic pulse (the weak probe wave) when it passes through the interaction volume containing the atomic medium in the presence of an intense laser field (the strong pump wave). Amplification is the net result of the competition between simulated emission and absorption of high-harmonic photons. In such situation the gain of the probe wave is proportional to the difference between the probability w_e for the emission of a probe-wave quantum and the probability w_a of its absorption by the atoms in the interaction volume,

$$G \sim \Delta w = w_e - w_a. \tag{1}$$

All available evidence shows that an atom initially in its ground state returns to the ground state when it emits the harmonic photon. Therefore, the squared matrix elements for emission and absorption of a harmonic photon are equal. Consequently, according to Eq. (1) the gain vanishes. This conclusion holds provided the atomic initial and final state are really identical, including the atomic center-of-mass motion. Owing to the recoil on the ion when the photon is emitted this is not strictly the case. Because, however, the value of this recoil is very small, the amplification can be appreciable only if the conditions of phase matching of the emitters in the propagation direction are satisfied [4].

In the present work the probabilities of the simulated emission and absorption were calculated in the frame of the strong field approximation [5]/ The influence of the ion recoil and the phase matching effect were taken into account. The final expression for the gain can be easily rewritten to number (per laser pulse) of spontaneous quanta of sth harmonic N_s [3, 6]:

$$G^{(s)} = -64\sqrt{\pi}\frac{s\hbar\omega(1-n(\omega))}{Mc^2}N_s\frac{1}{u_0F^2(u_0)}\frac{\partial}{\partial u_0}u_0^2F^2(u_0). \tag{2}$$

Here $G^{(s)}$ is a gain for the sth harmonics, $n(\omega)$ is the refractive index of the pump wave with frequency ω, M is the atomic mass. The function $F(u)$ is the Fourier-transform of the function which describes the spatial distribution of the atoms in the direction of the laser beam propagation. And, finally $u_0 = s\omega(1-n(\omega))L/(2c)$ where L is the length of the interaction volume in the propagation direction of the waves.

From the general expression (2) the gain was evaluated for the experimental data on N_s from [2] for the cases of the atomic jet and the hollow-core fiber. The parameters of the atomic beam (fiber) and the pump wave are taken from the experiment [2] too. The averaging of the gain (**??**) over the Gaussian spatial distribution of the pump-wave intensity was performed by using ADK formula [7] for the ionization rate.

The gain was investigated as a function of the atomic concentration on the axis of the jet or in the center of the fiber. An optimal conditions for the amplification of the probe wave correspond to relatively high atomic concentration then the number of spontaneous quanta decreases smoothly. At the density where the number N_s assumes its maximum, the gain is equal to zero [6]. The optimal value of the gain in the case of fiber ($G^{(s)}_{max} = 0,17$) is substantially larger than in the jet ($G^{(s)}_{max} = 0,04$), i.e. the gain in the fiber is substantially larger. There are two sources of this increase: (i) in the fiber the interaction length L is significantly longer ($L_{fib} = 1cm, L_{jet} = 0,1cm$) and (ii) the pump field in a fiber is more uniform than in the jet. As a result, the averaging over the laser focus does not reduce the gain as much as in the jet. Therefore, high-harmonic amplification should be investigated in an optical fiber rather than in an atomic jet.

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