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ATOMIC DYNAMIC FORCE PROCESS IN THE MEDIUM OF AN X-RAY LASER

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[Abstract] Studies of x-ray lasers is a vital topic at the present time. Carrying out these investigations will have very important effects on basic research and practical applications. The key to realizing x-ray lasers is finding out how to increase the gain coefficient. This paper emphasizes the microscopic atomic process in an x-ray laser medium, and diagnostic experiments recently conducted by the author and his colleagues with a soft x-ray streak camera.

After successfully observing the soft x-ray spontaneous radiation and amplification [1-5] in laboratories, researchers have had great interest in the study of x-ray lasers. The realization of x-ray lasers not only will exploit important purposes in fundamental research, but will also have an important influence on defense strategy. In basic scientific research, the x-ray laser can be considered as a probe with high penetration power; its distribution in time and space has coherent properties, thus providing a means of observation never before available in physics, chemistry, materials science, and even life sciences. For instance, in the window waveband of water (that is, the 26-40 Angstroms soft x-ray zone) the dynamic variation of proteolytic activity of live cells in water can be directly observed. In national defense, implementation of a nuclear-pumped x-ray laser can provide an energy beam apparatus with orientation properties, with important ramifications in future defense strategy. Moreover, the nuclear energy release apparatus with an orientation property can raise the efficiency of nuclear weapons systems; this will possibly be the direction of development of new-generation nuclear weapons; however, as demonstrated at present, the energy efficiency is very low for the amplification of spontaneous radiation of soft x-rays; this means that to a great extent the demands of practical applications cannot be satisfied. The wavelength of the soft x-ray is also longer for amplification of spontaneous radiation. Therefore, there are two main targets for current research on x-ray lasers: 1) explore new schemes for high-efficiency realization by adopting a high-power laser as the pump excitation energy source; design various types of novel macroscopic laser targets to promote the inversion of population numbers with the specific microscopic atomic power process. 2) Seek spontaneous radiation amplification of shorter-wavelength x-rays, such as the window waveband of water. In the following, some recent research achievements of the author and his colleagues are introduced.

I. Recent Research Achievements of the Author and His Colleagues

First, the operating principle of x-ray lasers is briefly explained. While lasing an x-ray laser, the working medium should include some specific ionized-state atoms in the plasma state. Since there are still no appropriate materials for a reflector lens in the x-ray waveband (how to prepare such materials is still much more difficult than the present state of knowledge, so the situation is still in the research stage), therefore the x-ray laser is of the amplification type of spontaneous radiation. When the pump-excited energy is imparted to the working medium, thus forming a plasma, it is required that the working medium should meet the following conditions:
(1) macroscopically, the uppermost-level empty working medium is dynamically assembled in a columnar structure in order to

facilitate self-radiation amplification. (2) At the same time, energy level population number inversion of the microscopic specific ions is formed. Whether it is successful for the macroscopic dynamic assembly is entirely determined by the design of the macroscopic target and the arrangement of the pump-excited energy source. Therefore, it depends on the specific process of microscopic atoms in order to effectively form the energy level population number inversion. The gain coefficient K of the x-ray self-radiation amplification is a function of the ionized-state atomic properties and corresponds to inversion of the energy level population number. That is,

$$K = (\lambda^3/8\pi)(\nu/\Delta\nu)(1/c\tau)\Delta N = (\pi e^2/mc\Delta\nu)f\Delta N, \quad (1)$$

In the equation, the wavelength λ, frequency ν, linewidth $\Delta\nu$, the excited-state lifetime τ and the emitted oscillator intensity f are quantities of the physical properties indicating the specific ionized-state atom. The energy level population inversion ΔN can be formed from the six following specific atomic processes: (1) Three-body combination process, a process that is the opposite of electron-collision ionization process. Based on this process, the self-radiation amplification of x-rays [1, 3, 4] is demonstrated. (2) The electron-collision process; mainly for this process, the self-radiation amplification [2 and 5] of soft x-rays has been demonstrated. (3) The light resonant excitation process, that is, the soft x-ray pump excitation for intense resonance in the working medium. (4) The photoionization process, that is, the utilization of intensely continuous x-ray pump excitation in the working medium. (5) The excitation process of resonant electric charge transfer. (6) The energy transfer process of ion resonance. Therefore, in order to seek the ideal x-ray laser scheme, it is required to select the appropriate working medium according to the process of atomic dynamic force; then the design of a macroscopic target is carried out.

On the atomic self-arrangement field-theoretic basis of relativity theory, the database [6, 7] of the ionized-state atomic energy level structure was built up. To the x-ray waveband of interest, all appropriate elements and the corresponding ionized-state atoms can be verified conveniently selected in order to serve the designing of the macroscopic target. For the transition x-ray of variation of the principal quantum number ($\Delta n \neq 0$), the wavelength is inversely proportional to the square of the extent of ionization. At the x-ray transition (generally via electron-collision excitation) of not varying the principal quantum number ($\Delta n=0$), the wavelength is inversely proportional to the extent of ionization. For the selected x-ray laser transition, the theoretical calculation program [8] of the relativistic atomic configuration interaction was drawn up, capable of precisely calculating the wavelength and the emitting oscillator intensity f. The linewidth formation mechanisms are mainly the excitation-state lifetime broadening, doppler broadening, electron-collision broadening, and Stark broadening. Stark broadening is relatively important in high-density plasma [9], the contribution to linewidth by Stark broadening will affect the determination of the energy gain coefficient. Corresponding to the energy level of the established structural database of the ionized-state atomic energy, the author and his colleagues systematically studied the electron-collision excitation process [10] and the x-ray absorption process [11]. The absorption cross-section of x-rays not only can be used to calculate ΔN in the pump-excitation scheme of the auto-electronic ionization, but also it is the essential foundation for calculating the consumption coefficient of an x-ray laser. Only when the consumption coefficient is smaller than the gain coefficient can an x-ray laser be realized.

Recently, a novel laser target design [12, 13] was proposed by the author and his colleagues; in the design, a microtube target was adopted in order to achieve higher electron density, thus intensifying the three-body combination process. The operating principle is as follows: first, a high-power laser stores the energy in the microtube target; under the restraint of the microtube target, a high-temperature, high-density plasma column is formed. Then through the radiation cooling and electron heat conduction process, the high-density plasma column is in the nonequilibrium compounding state. Since the electron density is very high, three-body compounding is the principal process at work. Three-body compounding predominantly forms the excitation state, thus leading to inversion of the energy level population number. Here a new result [14] of an x-ray spectrum with picosecond resolving power was obtained by the author and his colleagues. This result clearly explains the working principle of the three-body compounding scheme. The experiment employs a magnesium microtube target. The experiment was carried out at three institutes of the Chinese Academy of Sciences: the Shanghai Institute of Optics and Precision Machines, the Xi'an Institute of Optics and Precision Machines, and the Institute of Physics. All the experiments were carried out at the State High-Power Laser Physics (open to outside units) Laboratory. For measurement of the x-ray spectrum with time resolution, the recently developed scanning camera, capable of being dismantled, with a picosecond soft x-ray image converter tube (by the Xi'an Institute of Optics and Precision Machines of the Chinese Academy of Sciences) was adopted with a time resolving power capable of 33 picoseconds. The observation time development record of the scanning camera clearly indicates that the temperature is very high at the plasma column, therefore there is only hydrogen-like ions (such as the $Mg_{XII} 3 \rightarrow 1$ line) existing in the plasma column. In addition, as indicated by the scanning camera record, in the subsequent cooling compounding, the three-body compounding process predominantly generates the excitation state of the helium-like atoms (such as Mg_{XI}1snp, n = 5, 4, 3). Therefore, after emitting the hydrogen like $Mg_{XII} 3 \rightarrow 1$, 7.11 Angstroms) lines, the helium-like ($Mg_{XI}5 \rightarrow 1$, 7.31 Angstroms) line (Mg_{XI} $4 \rightarrow 1$, 7.47 Angstroms) line, and then, lastly, the (Mg_{XI} $3 \rightarrow 1$, 7.85 Angstroms) line subsequently appear. In such an intense compounding process, the inversion of energy level population numbers ($\Delta N \approx 2 \cdot 10^{18}$ cm^3) ($Mg_{XI}4 \rightarrow 3$) can be formed; it is expected that the x-ray self-amplification radiation of ($Mg_{XI}4 \rightarrow 3$) 154.6 Angstroms will be generated.

II. Discussion

In terms of experimental means, a complete set of a measurement system for picosecond-level time resolution x-ray spectra was constructed. Therefore, the atomic dynamic force process in the various x-ray laser schemes can be clearly monitored, thus determining the effect of various types of macroscopic target design. The measurement means for soft x-ray spectra (100 Angstroms waveband) is under development; in the not too-distant future, soft x-ray self-radiation amplification can be directly measured, and in this way one can more effectively determine the effect of various types of target designs. In theory, the preliminary data base of atomic physics and the simulation calculation program of the one-dimensional Lagrangian fluid simulated calculation program (WL code) [15] can be established for conducting the designing and simulation of various types of laser target experiments. If the experimental results of x-ray lasers have to be clearly analyzed, theoretical simulation is very important. The WL code has successfully simulated the dynamic force process [15] of implosion microsphere targets of high-power lasers [15]. This matches with the four division amplification x-ray shadow imaging diagnostic result (in other words, obtaining a two-dimensional x-ray shadow graph of four frames of different time periods within the nanosecond level), thus explaining the adaptation range of the one-dimensional simulation program. To obtain the optimal energy efficiency of an x-ray laser, in the evolutionary process of time and space, the laser working medium is dynamically assembled into a columnar shape; this is very important. Therefore, this is very useful in developing the picosecond-level frame division imaging technique. Finally, it is pointed out in research on high-power laser pump-excited x-ray lasers that further development and advancement of experiments and theoretical methods are very useful to the laser inertia-restrained fusion research. Laser inertia-restrained fusion is beyond the scope of this article, therefore it is not presented here; however, this is an important scheme for exploring the application of fusion energy.

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