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Atomic inner shell X-ray laser pumped by an X-ray free electron laser

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Today, ultra-high intensity X-ray field can be achieved by coupling with x-ray free electron laser and highly precision focusing optics. This intensity is as large as 10^{20}W/cm^2 and this is enough high for creating high density of K-shell electron vacancies in the solid materials. By using ultra-fast radiative transition from 2p to 1s, a femtosecond atomic X-ray laser is succeeded. In this paper, we discuss the characteristics of this laser with various experimental results.

1. Introduction

Peak power of x-ray free electron laser(XFEL) now exceeds GW level even at hard x-ray region. Due to the ultra-shortwave length features of hard x-ray, we can focus it down to 50nm diameter with precision x-ray optics. After that focus x-ray field is a high as 10^{20}W/cm^2. In the simple estimation of optical excitation rate of K-shell electron and relaxation rate of K-shell electron's hole, high density of K-shell vacancy atoms is achieved if the focused x-ray field is higher than 2×10^{19}W/cm^2. In this excited medium, we can expect large emissivity of Ka line due to very fast(~1fs) radiation rate. Previously, Rohringer succeeded Neon inner shell ionization laser with 1keV x-ray pulse from US–FEL facility (LCLS)[1]. In this case initial condition of the target medium is gas so that about 10^{19}cm^{-3} relatively smaller density of the inner shell excited condition was prepared. Yoneda achieved a saturable absorption[2] in Fe solid with 8keV hard x-ray photons in Japanese XFEL(SACLA). In this case, threshold intensity is about 2×10^{19}W/cm^2 and that number is matched to the theoretical predicted one. In this paper we will report achievement of a high gain condition of K alpha line after creation of high density excited state condition in the solid and performance of this Ka atomic lasers with various experimental conditions.

2. Gain estimation

The small-signal gain coefficient G of a laser is expressed with the following ,

$$G = N_u\sigma_{stim} - N_l\sigma_{abs} \approx N_u\sigma_{stim}F, \qquad (1)$$

where N_u and N_l are the number density of the upper and the lower states of the laser transition, σ_{stim} and σ_{abs} are cross sections of simulated emission and absorption between the laser transition levels. The F is the inversion factor. The cross-section σ_{stim} is rewritten by the following formula,

$$\sigma_{stim} = \frac{c^2}{8\pi\nu^2}\frac{1}{\Delta\nu}A_{ul} = \frac{\lambda^3}{8\pi c(\frac{\Delta\lambda}{\lambda})}A_{ul} \qquad (2)$$

where ν and λ are the frequency and wavelength of the laser, c is the speed of light, Δν and Δλ are frequency width and wavelength width of the laser, and A_{ul} is the spontaneous transition probability. The spontaneous rate of Ka emission is ~5×10^{14}s^{-1} in the middle Z atoms such as Cu, and Fe. If we assume spectral width of Ka laser is almost equal to the natural width of the emission(~3eV), more than 4×10^4cm^{-1} gain coefficient can be achieved with 30% ionization from the solid atoms and 30% inversion factor. To consider the length of the gain is as long as absorption length of the pump x-ray laser and is ~4μm. To couple with these values, we predict that the gain length product will be more than 15 so that it is real saturation laser expected in this experiment.

3. Experimental set up

In this study, a XFEL pulse from SACLA facility is used for pumping of the atomic laser. Nominal energy of XFEL is 6microJ and the pulse duration is 7fs respectively. By using two step focusing optics, we can achieved 50nm diameter focusing with 50μm Rayleigh length. The target we used are 10~30μm thickness foils of pure cupper, brass and cupronickel. Due to the relatively longer beam waist and enough short absorption length of the pump laser, we achieved uniform intensity condition inside solid target. In addition with this simple pumping scheme of single color beam, we also used two color pulses from SACLA laser facility to achieve pump and seed laser experiments.

The transition branches related to the Ka laser are shown in Fig1. The photon energy of the pump laser is tuned to the absorption edge of K-shell ionization. If we use the second seed beam, the photon energy of the second beam is tuned to those of Ka's. (Ka1(8048eV) and/or Ka2(8028eV)).

Output of the Ka line emission from the illuminated target is observed with Si crystal spectrometer which has a 2D CCD camera detector. Typical resolution of this system is about 0.1eV and the total observation range of the spectrum is about 40eV, if we use Si(111) as a dispersion element.

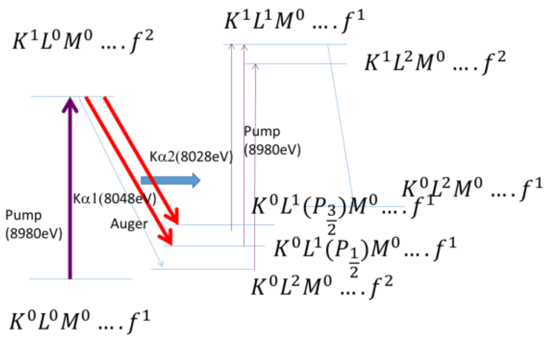

Fig1. Energy diagram

4. Experimental results

At first we checked target thickness dependence of the output energy of Ka emission. Totally, the energy of the Ka increases about 8 times if we change the target thickness from 5 to 20μm. At the 20μm, this increment is almost saturated. By using second seed pulse, both of Ka1 ($2p^{1/2}$->1s) and Ka2 ($2p^{3/2}$->1s) lines can be amplified, while only Ka1 lines was observed without the seed beam. The spectral width of the output Ka laser is four times narrower than those of Ka1 laser of the non-seeded condition. The minimum width of Ka laser spectrum is 1.7eV, it is slightly narrower than the emission width in natural electron beam excitation. By using Fourier transform law, the corresponding life time is about 1~2fs is slightly longer than the life time of cold materials (Auger process + fluorescence decay) Without the seed pulse, the spectrum has larger width and about 4~20eV. The wider spectrum is appeared with higher output Ka lasers. This widest spectrum is almost bridged between Ka1 and Ka2. This means gain width of this solid inner shell laser can be extended to 20eV so that 200as minimum pulse duration can be expected.

Conclusion

In the study, we achieve the inner shell atom x-ray laser at 8keV hard x-ray range. Up to now, that is most highest photon energy atomic lasers. With two color laser pulse, we succeed in seeding laser scheme in hard x-ray laser. This improvement of coherence will open new research field of nonlinear optics and quantum optics in hard x-ray area.

References

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