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Lasing potential of extreme-ultraviolet (EUV) light of nitrogen with a recombining plasma scheme

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A short-wavelength light source has been used for such industrial applications as nanostructure sciences and technologies[1)]. An extreme ultraviolet (EUV) light source is one of promising candidates for the next generation semiconductor lithography. The wavelength of EUV light is typically around ten to several tens nanometers. The EUV light has been experimentally generated by intense laser pulse irradiation and/or high current discharge. In general, hot dense plasma creation by discharge seems to be more efficient due to its compact and simple scheme compared with that by laser irradiation.

In this paper, hydrogen-like nitrogen is selected as one of EUV light emitters of which wavelength is 13.4 nm. The 13.4 nm EUV light comes from an optically allowed transition between $n\ell = 3\ell'$ and $2\ell''$ (Balmer-α), where n and ℓ respectively stand for a principal and an azimuthal quantum numbers. To get enough intensity of the EUV light in a recombining plasma scheme, nitrogen must be ionized to be a hydrogen-like state. After the creation of hot dense fully stripped nitrogen plasma, hydrogen-like nitrogen is populated by three-body recombination along with plasma expansion and cooling, leading to the creation of population inversion between those atomic states, and the lasing of Balmer-α.

Numerical calculation in this study focuses the lasing potential of nitrogen Balmer-α in a recombining phase. In the corresponding experiments to observe nitrogen Balmer-α up to now, there has been no lasing[2),3)]. In the numerical calculation in this paper, plasma conditions for GL≥5, where G and L respectively stand for a gain coefficient and plasma length, are obtained with the use of a time-dependent collisional-radiative (CR) model[4)]. In the model, doubly excited states, which are indispensable for the population kinetics model in recombining plasma, are implicitly considered in the framework of dielectronic-capture ladderlike (DL) processes by Fujimoto *et al.*[5)].

The DL-deexcitation process, for instance, $p + \mathrm{e} \rightarrow 1 + \mathrm{e}$ in the above article is briefly explained below, where p, e and 1 respectively denote a singly excited state, an electron in a continuum state and a ground state. At first, a singly excited hydrogen-like ion undergoes three-body recombination, forming a doubly excited state pq : $p + \mathrm{e} \rightarrow pq$, where q denotes the level of an outer bound electron ($q \gg p$). At high electron density, collisional processes are dominant on pq, and the state is collisionally deexcited before autoionization and/or radiative decay. Proceeded to further deexcitation: $p(q\text{-}1) \rightarrow p\,(q\text{-}2) \cdots \rightarrow pr\ (r \ll q)$, an atomic state pr is finally autoionized to be a ground-state hydrogen-like ion: $pr \rightarrow 1 + \mathrm{e}$. This procedure could be regarded as deexcitation of a hydrogen-like ion: $p + \mathrm{e} \rightarrow 1 + \mathrm{e}$, which implicitly includes doubly excited states as intermediate states.

For the sake of continuous collisional deexcitations, an outer electron must be bound in an atomic level where collisional processes are dominant. An atomic level where collisional processes balance with autoionization and radiative decay is called a collision limit or a Griem's limit[5)].

In this paper, discussions are also devoted to the effects of unresolved satellite lines around the Balmer-α on the time-dependent gain properties[6)]. Unresolved satellite lines come from doubly excited states $n\ell n'''\ell'''$ of which outermost bound electron is in a high-lying orbital. Since the energy levels of $n\ell n'''\ell'''$ are near in Local Thermal Equilibrium with a singly excited state $n\ell$, population inversion between $3\ell' n'''\ell'''$ and $2\ell'' n'''\ell'''$ is also created whenever that between $3\ell'$ and $2\ell''$ is done in recombining plasma. The stimulated emission, which does not mean "lasing", of unresolved satellite lines caused by Balmer-α amplified to some extent affects the creation of population inversion between $3\ell'$ and $2\ell''$.

Finally, some numerical results of radiation transport coupled with the CR-model to see amplification of the Balmer-α will be presented.

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