Specification for pumping x-ray laser with ionizing radiation

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It is shown that pumping of a medium with an atomic number $z \approx 30$ by short-wavelength ($\lambda_p \lesssim 0.1$ nm) electromagnetic radiation of $\sim 10^{15}$–10^{16} W/cm² intensity for a time $t_p \gtrsim 30$ nsec should, in principle, result in stimulated emission due to $n_i = 5, 4 \to n_f = 3$ transitions between the hydrogenic states of multiply ionized ions (giving rise to laser emission at $\lambda_l \sim 1$–2 nm). The active medium may be formed during irradiation from, for example, a copper or brass wire $l \sim 1$ m long with an initial radius $r_0 \lesssim 0.3$ mm.

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Recombination nonequilibrium of a plasma can be maintained by an external ionizing source (for example, a beam of electrons or of short-wavelength electromagnetic radiation), as shown in §16 in Ref. 1. Conditions suitable for lasing may be established directly during the action of such an ionizing source. The situation is then basically similar to that discussed in the case of plasma lasers emitting visible radiation, but so far the discussions relating to the short-wavelength range (laser emission at $\lambda_l < 50$ nm) have been confined to pumping in which the energy deposition and cooling of electrons are separated significantly in time. This has been due to the absence of laboratory sources of ionizing radiation with a flux density sufficient to pump transitions in the short-wavelength range. We shall consider "exotic" sources[2] and estimate the requirements in respect of the flux of ionizing x rays needed to achieve laser emission at wavelengths of 1–2 nm.

We shall consider population inversion[1,3] of hydrogenic levels with c = 5, 4, and 3. Inversion as a result of $n_i = 5, 4 \to n_f = 3$ transitions appears because the final (lower) level n_f is depopulated more rapidly than the initial (upper) levels n_i. We cannot expect inversion relative to $n_f = 2$ because of reabsorption of the radiation due to the $2 \to 1$ transition when pumping with fast secondary electrons induces the $1 \to 2$ transition (see §16 in Ref. 1). The $n_i = 5, 4 \to n_f = 3$ transitions correspond to $\lambda_l \sim 1$–2 nm when the nuclear charge is $Z \approx 30$. For example, if $Z = 26$ (iron), we have $\lambda_{43} = 2.77$ nm and $\lambda_{53} = 1.9$ nm; in the case of $Z = 29$ (copper), we obtain $\lambda_{43} = 2.23$ nm and $\lambda_{53} = 1.52$ nm; if $Z = 30$ (zinc), we find that $\lambda_{43} = 2.08$ nm and $\lambda_{53} = 1.42$ nm. The ionization potentials $J_Z = 13.6Z^2$ (eV) of the H-like ions of these elements are $J_{Fe} = 9.2$ keV, $J_{Cu} = 11.4$ keV, and $J_{Zn} = 12.2$ keV. In the case of continuous pumping we have to ensure that the pump photon energy $\hbar\omega_p$ exceeds J_Z. This corresponds to a pump wavelength $\lambda_p \sim 0.1$ nm and to an effective source temperature $T_s \gtrsim 10$ keV.

Inversion as a result of the $n_i = 5, 4 \to n_f = 3$ transitions can be expected for relatively low values of the electron density and temperature in a plasma (see Figs. 5 and 3 in Ref. 1): $N_e \sim (5-10)\times 10^{11} Z^7$ cm$^{-3} \sim 10^{22}$ cm^{-3}, $T_e \sim (1-2)Z^2$ eV ~ 1–2 keV. If in the initial state the active medium is a solid (for example, a brass wire of $r_0 = 0.3$ mm radius), the reduction in the electron density by expansion from $N_{e0} \sim Z \times 10^{22}$ cm$^{-3} \approx 3\times 10^{23}$ cm^{-3} to $N_e \sim 10^{22}$ cm^{-3} at a velocity $v_T \sim \sqrt{2T_e/Am_p} \sim \sqrt{T_e/m_p Z} \sim 0.5 \times 10^7$ cm/sec ($A \approx 2Z$, $m_p = 1.6\times 10^{-24}$ g) takes place in a time $t_{exp} = r_0/v_T (N_{e0}/N_e) \sim 30$ nsec.

The duration of pumping t_p should exceed the time required for expansion to the appropriate electron density: $t_p > t_{exp}$). It should be noted that in the case of pumping by thermal ionization and subsequent cooling,[1] the pump time does not have a lower limit but an upper one ($t_p < t_{exp}$).

The threshold intensity of the ionizing radiation I_p in the case of equal numbers of ionization and recombination events is related to the threshold value of the gain $\varkappa_{th}$ by

$$\varkappa_{th} \approx (\lambda_l^2/16\Delta\omega)(N_{Z-1}\sigma_{ph} I_p/\hbar\omega_p),$$

where $\Delta\omega$ is the effective line width; σ_{ph} is the photoionization cross section of an ion with a charge $Z-1$; $N_{Z-1} \sim N_Z \sim N_e/Z \sim 3\times 10^{20}$ cm^{-3}.

We shall assume that the wire length is $l \sim 1$ m and that $\varkappa_{th} \sim 10/l \sim 0.1$ cm^{-1}. Overestimating somewhat the Stark line width

$$\Delta\omega = 11 \frac{\hbar}{m_e}(n_f^2 - n_i^2)\left(\frac{N_e}{Z}\right)^{2/3} \sim \begin{cases} 5\cdot 10^{16}\ \text{sec}^{-1} \text{ for } 4\to 3, \\ 10^{16}\ \text{sec}^{-1} \text{ for } 5\to 3, \end{cases}$$

we find that the conditions for the two transitions are

$$\sigma_{ph}\frac{I_p}{\hbar\omega_p} > \begin{cases} 5\cdot 10_8\ \text{sec}^{-1} \text{ for } 4\to 3\ (Z=30), \\ 3\cdot 10^9\ \text{sec}^{-1} \text{ for } 5\to 3\ (Z=30). \end{cases}$$

If $\sigma_{ph} \sim 10^{-21}$ cm², $\hbar\omega_p \sim 10$ keV $\approx 1.6\times 10^{-15}$ J, we find that $I_p \sim 10^{15}$ W/cm² for the $4\to 3$ transition and $I_p \sim 5\times 10^{15}$ W/cm² for the $5\to 3$ transition ($Z = 30$). At a distance of ~1 m from the pump source this intensity corresponds to the evolution of 10^{14} J in 50 nsec if the hard radiation carries more than 10% of the energy. The divergence of the laser beam should then be $\varphi = v_T t_{exp}/l \sim 10^{-3}$ rad.

It follows from the above estimates that laser emission at $\lambda_l \approx 1.4$ nm considered in Ref. 2 may indeed occur (the closest to this wavelength is the $5\to 3$ transition in zinc, as discussed above). However, the information given in Ref. 2 is quite insufficient to judge the feasibility of the experiment itself and to interpret it more specifically. An analysis of the dynamics of forced expansion of the plasma under the action of high-power electromagnetic radiation, similar to that given in Refs. 4 and 5, becomes additionally interesting in connection with the above proposal.

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CHRONICLE

First International School on Coherent Optics and Holography (Prague, September 1–12, 1980)

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A brief review is given of papers presented at the First International School on Coherent Optics and Holography (Prague, 1980) and at the Second Czechoslovak Conference on Integrated Optics. The School was organized in sessions on coherence of light, fiber optics, integrated optics, holography, optical diagnostic methods, and adaptive optics.

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The First International School on Coherent Optics and Holography, designed for young scientists from the Socialist Comecon countries, was held on September 1–12, 1980 in Prague, the capital of Czechoslovakia, the "golden city with one hundred towers." The organizers were the P. N. Lebedev Physics Institute of the USSR Academy of Sciences, Scientific Council of the USSR Academy of Sciences on Coherent and Nonlinear Optics, National Committee on Optics of the Czechoslovak Academy of Sciences, Nuclear and Engineering-Physics Departments of the Prague Technical University, Institute of Radio Engineering and Electronics of the Czechoslovak Academy of Sciences, and others. The Rector of the International School was Academician A. M. Prokhorov and the Chairman of the Organizing Committee was Academician of the Czechoslovak Academy of Sciences B. Kvasil.

The School was divided into six sessions on coherence of light, fiber optics, integrated optics, holography, optical diagnostic methods, and adaptive optics. A total of 45 lectures and 68 papers were read. The number of participants was 242, including 116 from Czechoslovakia, 77 from the Soviet Union, 21 from Poland, 15 from Bulgaria, 9 from East Germany, and 4 from Hungary.

The Second Czechoslovak Conference on Integrated Optics was held simultaneously (September 8–10); 4 papers and 16 other communications were presented at this Conference.

1. COHERENCE OF LIGHT

J. Peřina (Olomouc University) devoted the introductory part of his lecture on "Coherence properties of optical fields" to reviewing the main stages of the development of statistical optics. He gave a quantum definition of correlation functions in optics, discussed ways of determining them, and gave various methods for describing optical fields. He paid special attention to the statistics of photons. He described chaotic, coherent, and anticoherent fields, the last being characterized by a negative value of the variance of the number of photons. The correlation functions of the intensity of anticoherent fields manifest the photon antibunching effect. He also gave the results of observation of photon antibunching in experiments involving resonant fluorescence in atomic vapors.

J. Peřina gave also a paper on "Statistics of photons in nonlinear optical processes" in which he reviewed briefly the quantum-statistical properties of such processes as multiphoton absorption and emission, generation of higher harmonics, parametric amplification and oscillation, and hyper-Raman scattering. These nonlinear phenomena depend strongly on the initial statistical properties of the radiation. In discussing the photocount statistics the author discussed determination of their variance for the nonlinear processes just mentioned and demonstrated the possibility of generating optical fields in the anticorrelation state when the photon antibunching effect is observed. He pointed out

