THE SYSTEM OF ENCLOUSED OPTICAL CAVITIES AS A TOOL FOR LASER PHOTONS STORING

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The calculation of the system consisting of two optical cavities enclosed one into another is performed in the plane-wave approximation. It is shown that under definite conditions one can obtain an enhancement of the electromagnetic field in the internal cavity as compared to the case of direct excitation of the cavity with an electromagnetic wave of the same amplitude. The comparative analysis of these two approaches is carried out. We suppose to apply the proposed system with moderate-reflectivity mirrors (*R*=0.99) for accumulating laser photons in the optical cavity of the X-ray source LESR-N100 based on Compton scattering of the laser beam on relativistic electrons stored in the ring.

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1. INTRODUCTION

To attain the goal parameters for monochromatic X-ray source based on Compton scattering one has to develop the effective laser-optical system that should provide in the interaction point (IP) a continuous sequence of short (≤10 ps) laser bunches with a density of N_{ph}~ $10^{23}m^{-2}$ and a high repetition frequency. For the LESR – N100 that is under development at the NSC KIPT the repetition frequency is 57 MHz. To obtain the required number of photons (N~10^{15}) in bunches directly from the pulsed laser at such a frequency is a rather complicated task because one needs a laser with an average power of ~12 kW. For the time being the high frequency lasers with bunch densities two order less than required are the state of art devices.

The solution of the problem is found in storage of laser pulses in resonance optical systems, the simplest being a two-mirror cavity with high-reflectivity mirrors (r^2≥0.999) [1]. The accumulation factor in such a cavity attains the value of 10^3. At present time the mirrors with reflectivity higher than 0.9999 are developed [2] and higher accumulation factors are anticipated.

To obtain the required laser bunch size in the IP the optical cavity with high focusing has to be used. Together with a rather large cavity length (several meters for small beam interaction angles α~3^0…5^0) it means a necessity to use large-aperture mirrors in order to minimize diffraction losses in the cavity. A commercial availability of such large-aperture high-reflectivity mirrors is questionable.

Another disadvantage of high-reflectivity mirrors is their lower radiation resistance (or breakdown thresholds) in comparison to the traditional medium reflectivity mirrors [3]. This factor limits the mean energy stored in the cavity.

In this paper we consider the alternative photon storage systems incorporating medium-reflectivity mirrors (r^2~0.99) that ensures the accumulation factor of ~10^3…10^4

These systems are studied theoretically in the plane-wave approximation.

2. THE SYSTEMS OF ENCLOSED CAVITIES

The systems considered are schematically presented in fig. They consist of a pair of optical cavities enclosed one into the other.

2.1. LINEAR CAVITY

The four-mirror linear structure that stores laser photons in the internal cavity is presented in fig.1a. The essential part of photons escaped from the internal cavity through the mirrors is intercepted with external reflectors, and they are brought back into the storing cavity through the same mirrors. This decreases the laser power required to support a constant intensity of the stored laser bunch thus increasing the accumulation factor of the system as compared with a two-mirror cavity with the same reflectors.

The complex amplitudes of electromagnetic waves in the regions of interest of the symmetric linear four-mirror resonance structure are given with the following relations:

- the wave amplitude in the storing cavity

$$\dot{B} = \frac{\dot{T}}{1-\dot{R}^2\exp(-2ikl_0)}\,, \tag{1}$$

- the amplitude of the reflected wave

$$\dot{\Re}' = \frac{\dot{R}\left[1-\dot{R}\mathrm{e}xp(-2ikl_0)/\dot{R}^*\right]}{1-\dot{R}^2\exp(-2ikl_0)}\,, \tag{2}$$

- the amplitude of the transmitted wave

$$\dot{T}' = \frac{\dot{T}^2\exp(-ikl_0)}{1-\dot{R}^2\exp(-2ikl_0)} \tag{3}$$

where:

$$\dot{R} = \frac{\dot{r}\left[1-\dot{r}\exp(-2ikl_1)/\dot{r}^*\right]}{1-\dot{r}^2\exp(-2ikl_1)} \tag{3a}$$

$$\dot{T} = \frac{\dot{t}^2\exp(-ikl_1)}{1-\dot{r}^2\exp(-2ikl_1)} \tag{3b}$$

are the reflection and transmission factors, respectively, for cavities formed by pairs of right and left reflectors; the symbol "*" denotes a complex conjugate.

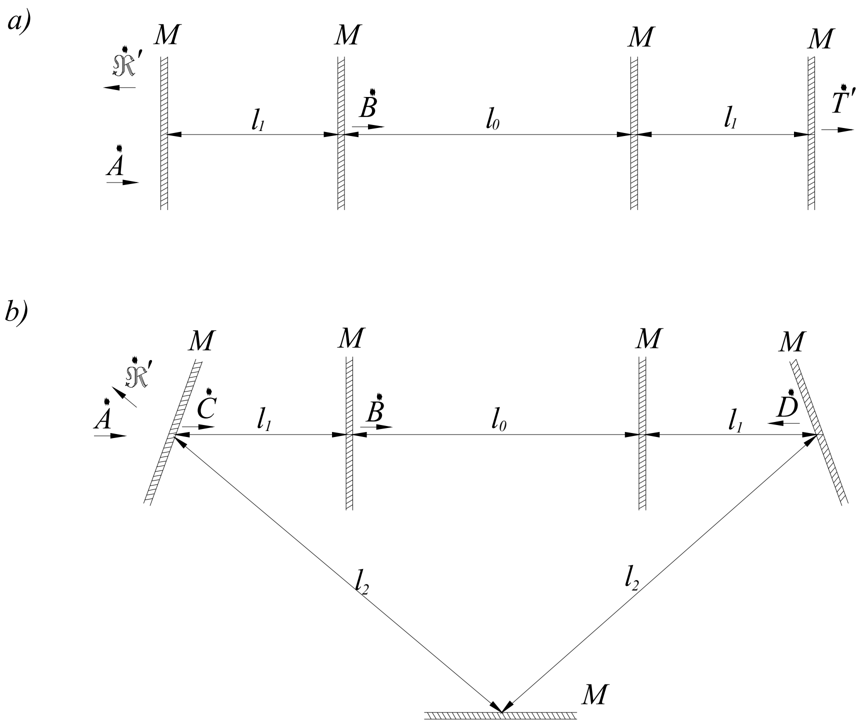

Fig. The systems of enclosed optical cavities: a) – the linear symmetrical four-mirror structure; b) - the structure with an external ring cavity. Notation: M – mirrors with reflectivity $\dot r$ and transit factor $\dot t$; l_0, l_1 and l_2 are distances between corresponding reflectors; $\dot A$ $\dot B$, $\dot C$, $\dot D$, $\dot{\Re}'$, $\dot T'$ - the complex amplitudes ($\dot A = 1$) of the waves propagating in directions denoted by arrows

The magnitudes squared of the values presented by the relations (1) – (3) describe the energy transferred by electromagnetic waves in the corresponding directions. They are the accumulation factor, reflection factor and transmission factor of this resonance system, correspondingly. The accumulation factor attains maximum value if the resonance condition for internal cavity with length l_0 is fulfilled. The reflectors of this cavity are anti-resonators formed by pairs of the left-hand and right-hand mirrors. The maximum value is given by:

$$K_{ph}^{\max} = \left(1 + r^2\right)^2 / \left(1 - r^2\right)^2 , \qquad (4)$$

where r= $|\dot r|$.

The accumulation factor for the traditional two-mirror cavity can be obtained from the equation (1) by substituting values $\dot R$ and $\dot T$ with corresponding reflectivity factor $\dot r$ and transmission factor $\dot t$ for reflectors. It is given by:

$$K_{ph.OR}^{\max} = \left(1 - r^2\right)^{-1} \qquad (5)$$

By comparison of equations (4) and (5) one can see that the gain in accumulation factor for the linear four-mirror system is essential and reaches ~400 for medium-reflectivity (r^2=0.99) mirrors.

Considering a strong dependence of the parameters of compound reflectors formed by pairs of left-hand and right-hand mirrors one can deduce without analyzing the dispersion equation that such a structure is applicable only for storing continuous photon beams.

2.2. SYSTEM OF ENCLOSED CAVITIES WITH AN EXTERNAL RING STRUCTURE

The system of enclosed optical cavities with an external ring structure is presented in fig.1,b. Unlike the case of linear structure the photons lost by the accumulating cavity are returned into the latter not through the same mirrors but they are restored from the opposite directions by using the external reflectors to form a new additional path.

For this system we obtained the following expressions for electromagnetic fields in the regions of interest:

- the wave amplitude inside the storing cavity

$$\dot B = \dot T \exp[-ik(l_1 - l_0)] \times \frac{1 - \dot{\Re}\dot T \exp(-ikL) + \dot{\Re}\dot R \dot r \exp[-ik(L + l_0)]}{\left[1 - \dot{\Re}\left(\dot T + \dot R\right)\exp(-ikL)\right]\left[1 - \dot{\Re}\left(\dot T - \dot R\right)\exp(-ikL)\right]} , \quad (6)$$

- the amplitude of the wave propagating clockwise in the ring cavity

$$\dot C = \frac{\dot t \cdot \left[1 - \dot{\Re}\dot T \exp(-ikL)\right]}{\left[1 - \dot{\Re}\left(\dot T + \dot R\right)\exp(-ikL)\right]\left[1 - \dot{\Re}\left(\dot T - \dot R\right)\exp(-ikL)\right]} , \quad (7)$$

- the amplitude of the wave propagating anticlockwise in the ring cavity

$$\dot D = \frac{\dot t \dot{\Re} \dot R \cdot \exp(-ikL)}{\left[1 - \dot{\Re}\left(\dot T + \dot R\right)\exp(-ikL)\right]\left[1 - \dot{\Re}\left(\dot T - \dot R\right)\exp(-ikL)\right]} , \quad (8)$$

- the amplitude of the reflected wave

$$\dot{\Re}' = \frac{1}{\dot r^*}\left\{1 - \frac{\dot t^2\left[1 - \dot{\Re}\dot T \exp(-ikL)\right]}{\left[1 - \dot{\Re}\left(\dot T + \dot R\right)\exp(-ikL)\right]\left[1 - \dot{\Re}\left(\dot T - \dot R\right)\exp(-ikL)\right]}\right\} , \quad (9)$$

where $\dot R$ and $\dot T$ are defined by equations (3a,b) with substituting l_1 with l_2; $\dot{\Re} = \dot{r}^3$; $L=2(l_1+l_2)$ is the length of the external part of the ring system.

If the resonance conditions are fulfilled for the internal cavity then $\dot{R} = 0$. This simplifies essentially the field structure in the system under consideration. Moreover, in the external part of the ring structure only traveling wave mode is allowable ($\dot{C} \neq 0, \dot{D} = 0$). The expressions (6) and (9) are reduced to:

$$\dot{B} = -\frac{\exp[-ik(l_1 - 2l_0)]}{1 + \dot{\Re}\exp[-ik(L - l_0)]} \quad (10)$$

$$\dot{\Re}' = \frac{1}{\dot{r}^*}\left[1 - \frac{t^2}{1 + \dot{\Re}\exp[-ik(L - l_0)]}\right] \quad (11)$$

It was shown above that the field amplitude squared in the internal cavity defines the accumulation factor of the system. Thus, the magnitude squared of the expression (10) presents the accumulation factor of the ring cavity system that reaches its maximum value at the resonance:

$$K_{ph.K}^{\max} = \left(1 - r^3\right)^{-2} \quad (12)$$

It is seen from comparison of equations (12) and (5), that the ring cavity system ensures a higher accumulation factor than two-mirror cavity. The gain reaches value of 45 for medium-reflectivity (r^2=0.99) mirrors.

The reflection factor for the ring cavity system would not exceed 0.1 as follows from expression (11). By matching the system input one can, in principle, decrease it down to zero, thus increasing the accumulation factor up to ~10^4.

The analysis of the dispersion equations for the internal cavity:

$$1 - \dot{r}^2\exp(-2ikl_0) = 1 - r^2, \quad (13)$$

and for the ring structure:

$$1 + \dot{r}^3\exp[-ik(L - l_0)] = 1 - r^3 \quad (14)$$

shows that they can have the same frequency spectrum. It can be realized by using the frequency-independent reflectors and by fixing $L=3l_0$, i.e. the length of the external ring structure should be twice the length of the internal cavity. The natural frequencies of these systems are separated by the value:

$$\Delta f = \frac{c}{2l_0} \quad (15)$$

Thus, this system can be applied for storing both continuous and pulsed laser beams.

3. CONCLUSIONS

The performed studies show that the system of enclosed cavities with an external ring structure can provide accumulation factors up to 10^4 even for the case when it incorporates medium-reflectivity mirrors (r^2=0.99). Such mirrors are more advantaged than high-reflectivity ones because of their higher radiation resistance, low prices and commercial availability. We consider this system as the most promising for using in X-ray sources based on Compton scattering of the laser light on the electrons stored in the accelerator ring.

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СИСТЕМА ВЛОЖЕННЫХ РЕЗОНАТОРОВ КАК УСТРОЙСТВО ДЛЯ НАКОПЛЕНИЯ ЛАЗЕРНЫХ ФОТОНОВ

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В работе в приближении плоской волны проведен расчет системы вложенных один в другой оптических резонаторов. Показано, что при определенных условиях возможно получение усиления электромагнитного поля во внутреннем резонаторе по сравнению с непосредственным его возбуждением электромагнитной волной той же амплитуды. Предполагается использовать этот эффект для накопления числа фотонов в оптическом резонаторе источника рентгеновского излучения на основе обратного комптоновского рассеяния LESR-N100. Проведен сравнительный анализ результатов, полученных с помощью данного подхода и подхода, основанного на непосредственном возбуждении оптического резонатора лазером.

СИСТЕМА ВКЛАДЕНИХ РЕЗОНАТОРІВ ЯК ПРИСТРІЙ ДЛЯ НАКОПИЧУВАННЯ ЛАЗЕРНИХ ФОТОНІВ

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У роботі у наближенні плоскої хвилі виконані розрахунки системи вкладених один в другий оптичних резонаторів. Доведено, що за окремих умов можливо досягти підсилення електромагнітного поля у внутрішньому резонаторі у порівнянні з його прямим збудженням електромагнітною хвилею тієї же амплітуди. Пропонується застосувати цей ефект для накопичування фотонів в оптичному резонаторі джерела рентгенівського випромінювання на засаді комптонівського розсіювання LESR-N100. Зроблений порівняльний аналіз результатів, одержаних для запропонованої системи та схеми, заснованої на прямому збудженні оптичного резонатора лазером.