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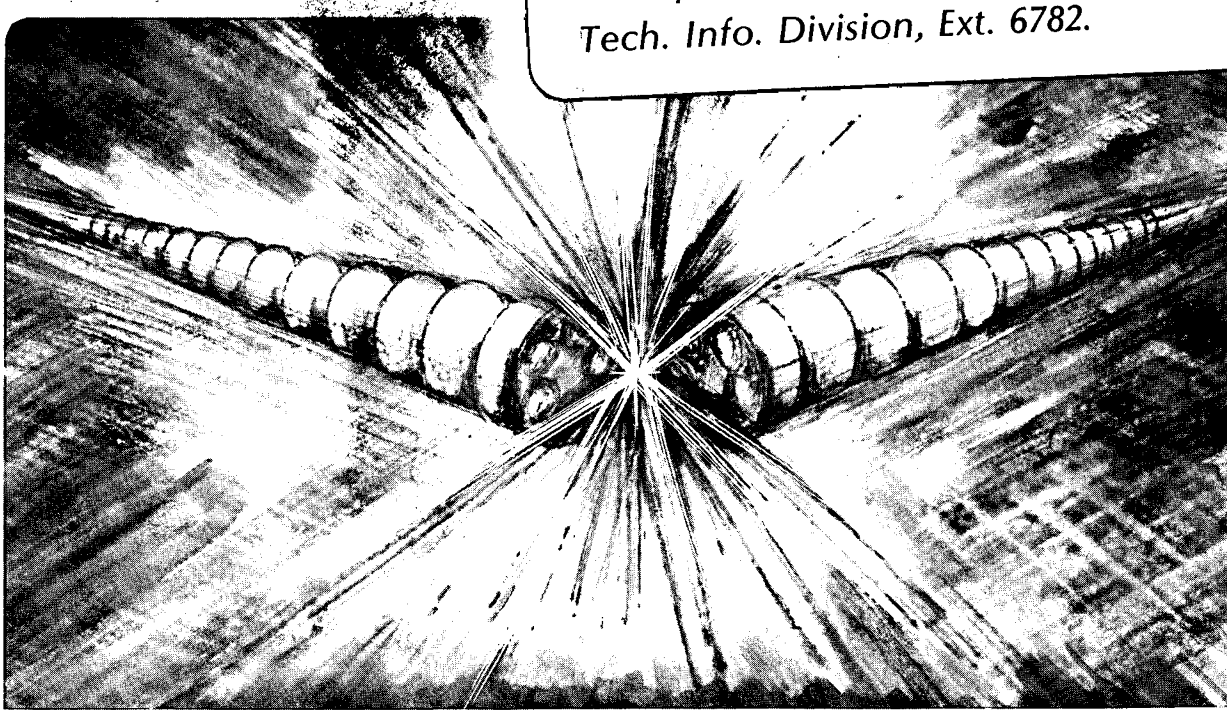

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## Abstract

A novel configuration of free electron laser system is proposed that is capable of generating coherent radiation whose polarization is arbitrary and rapidly adjustable. The magnet configuration is similar to that of the optical klystron except that the undulators are placed perpendicular rather than parallel to each other. The gain of the system is analyzed in the small signal regime, and is found to be similar to that of the optical klystron. The polarization of the laser radiation at maximum gain is found to be different from the polarization of the spontaneous radiation.

## Introduction

Recently, a two undulator system was proposed(1) that is capable of producing spontaneous radiation with rapidly adjustable polarization. If the system is placed in an optical resonator, it will operate as a free electron laser.(2) The purpose of this paper is to study the operation of this new free electron laser system in the small signal regime. The analysis of this system requires a generalization of the usual free electron laser theory to include the effect of the polarization.

The magnet system is shown in Fig. (1). It consists of two identical parts, the second of which is rotated 90° relative to the first one. Each

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part consists of an N period planar undulator of period length $\lambda_u$ and an additional magnet shown as the shaded block in the figure. The additional magnet was named as the modulator in ref. (1) because its sole purpose there was to modulate the polarization of the spontaneous radiation. Incorporated in a free electron laser system, the magnet also serves the function of introducing a strong dispersion in the electron path. Hence it will be referred to as the dispersion-modulation magnet in this paper.

Spontaneous Radiation

The spontaneous radiation due to an electron passing through the device has the following polarization vector:

$$\underset{\sim}{\varepsilon} = \frac{1}{\sqrt{2}} \left( \hat{x} + e^{i\alpha} \hat{y} \right) , \qquad (1)$$

where

$$\alpha = \frac{\pi}{\lambda\gamma^2} \left( N\lambda_u(1+K^2/2) + \lambda_M(1+K_M^2/2) + D \right) . \qquad (2)$$

In the above, $\lambda$ is the radiation wavelength, $\gamma$ is the electron energy divided by its rest energy, $D = D_1 + D_2$, and $K$ and $K_M$ are the deflection parameters of the undulator and the dispersion-modulation magnet respectively. The deflection parameters are defined to be .934 times the peak magnetic field in tesla times the period length in cm. For simplicity, the magnetic fields of both the undulator and the dispersion-modulation magnet are assumed to be sinusoidal. The radiation is peaked at

$$\lambda = \lambda_u(1+K^2/2)/(2\gamma^2 n) , \qquad (3)$$

where $n$ is a positive integer. In this paper only the first harmonic $n = 1$ will be considered.

In the above, electrons are assumed to be perfectly on axis. The effects due to a finite angular divergence and an energy spread are considered in ref. (1).

Equation (1) corresponds to the general case of elliptically polarized radiation. As $\alpha$ varies, the polarization ellipse changes as shown in Fig. (2). Thus one can obtain any desired polarization. The phase $\alpha$ can be changed either by changing the distance $D$ mechanically or by changing the magnetic field of the dispersion-modulation magnet. The latter method can produce a polarization modulation with a rate $\gtrsim 1$ kHz.

If the two undulators are placed parallel rather than perpendicular to each other, the system becomes the well-known optical klystron.[3] In the optical klystron, the polarization remains constant as $\alpha$ changes. However, the intensity of the spontaneous radiation is modulated[4] by a factor $1 + \cos\alpha$.

## Polarization Effect in Free Electron Laser

The small signal gain $G$ of a free electron laser system is given by the following general form:

$$G \propto \frac{\partial}{\partial\gamma}\frac{dI}{d\Omega d\omega}\ , \tag{4}$$

where $dI/d\Omega d\omega$ is the spontaneous radiation intensity. This relation can best be obtained from the two well-known theorems derived by Madey[5]. Usually, the polarization is obvious and is not specified in Eq. (4). In the present case, however, the polarization of the spontaneous radiation depends on $\gamma$, and thus cannot be the same as that of the laser radiation which must be independent of $\gamma$. Thus the polarization vector $\varepsilon_0$ of the laser radiation enters as an unknown parameter in the calculation of the gain. The most general form that $\varepsilon_0$ can take is

$$\underset{\sim}{\varepsilon}_0 = \sqrt{1-r^2}\,\hat{x} + r\,e^{i\alpha_0}\,\hat{y}\,. \tag{5}$$

The gain $G$ becomes a function of $\underset{\sim}{\varepsilon}_0$, and Eq. (4) is then generalized as follows:

$$G(\underset{\sim}{\varepsilon}_0) \propto \frac{\partial}{\partial\gamma}\frac{dI(\varepsilon_0)}{d\Omega d\omega}\,. \tag{6}$$

Here $dI(\underset{\sim}{\varepsilon}_0)/d\Omega d\omega$ is the partial intensity of the spontaneous radiation whose electric field vector is along the direction specified by $\underset{\sim}{\varepsilon}_0$.

The parameters $r$ and $\alpha_0$ is determined by requiring that the gain is maximized. From Eqs. (1) and (5) it is intuitively clear that the maximum in the present system will occur at $r = 1/\sqrt{2}$. The polarization is therefore given by

$$\underset{\sim}{\varepsilon}_0 = \frac{1}{\sqrt{2}}\left(\hat{x} + e^{i\alpha_0}\,\hat{y}\right)\,. \tag{7}$$

Thus $\alpha_0$ is the only additional parameter of the theory.

## Gain Analysis

The explicit formula for gain is given by

$$G(\varepsilon_o) = \frac{8\pi^2 \rho_o r_o \lambda_u^2 N^3 K^2}{\gamma^3} F_f \left[ J_o\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)\right]^2$$

$$\times - \frac{d}{dx}\left[\left(\frac{\sin x/2}{x}\right)^2 \left(1 + \cos(\alpha-\alpha_o)\right)\right] . \tag{8}$$

In the above, $\rho_o$ is the peak electron density, $r_o$ is the classical electron radius, $F_f$ is the filling factor and

$$x = 4\pi N \frac{\gamma-\gamma_r}{\gamma_r} , \tag{9}$$

where $\gamma_r$ is the resonant energy

$$\gamma_r^2 = \frac{(1+K^2/2)\lambda_u}{2\lambda} . \tag{10}$$

From Eqs. (2) and (9), one finds that $\alpha$ is the following function of $x$:

$$\alpha = 2\pi\left(N + N_d\right) - x\left(1 + \frac{N_d}{N}\right) . \tag{11}$$

Here $N$ is a quantity introduced in the analysis of optical klystron[4], and is given by

$$N_d = \frac{\lambda_M(1+K_M^2/2)+D}{\lambda_u(1+K^2/2)} . \tag{12}$$

Equation (8) is very similar to the corresponding formula for the case of the optical klystron, which can be obtained simply by replacing the factor $1 + \cos(\alpha-\alpha_0)$ by $2(1+\cos\alpha)$. Thus the gain in the present case can be increased by making the ratio $N_d/N$ large, just as in the case of the optical klystron.

To find the maximum gain, one needs to study the last factor in Eq. (8) which is

$$F(x,\alpha_0) = \frac{1 - \cos x - (x/2)\sin x}{x^3}\left(1 + \cos(\alpha-\alpha_0)\right)$$

$$- \left(1 + \frac{N_d}{N}\right)\left(\frac{\sin x/2}{x}\right)^2 \sin(\alpha-\alpha_0) \ . \tag{13}$$

In the limit of weak dispersion, $N_d/N \to 0$, the maximum value of $F$ is $F_M = .27$ and occurs at $x = 1.02$ and $\alpha - \alpha_0 = -1.4$. In the other limit of strong dispersion, $N_d/N \to \infty$, the maximum value is $F_M = N_d/4N$ and occurs at $x = 0$ and $\alpha - \alpha_0 = -\pi/2$. Thus one obtains the surprising result that the polarizations of the laser radiation and the spontaneous radiation are different. Thus, for example, the polarization of the laser radiation at maximum gain is circular when the polarization of the spontaneous radiation is linear.

The discussions in this paper indicate that the proposed system is potentially a very interesting free electron laser device. Its small signal gain can be enhanced by making the magnetic field of the dispersion-modulation magnet large. The polarization of the laser radiation can be modulated rapidly by modulating the field of the dispersion-modulation magnet.

Acknowledgements

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## References

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## Figure Captions

Fig. 1. Schematic of the system.

Fig. 2. Evolution of the polarization ellipse as $\alpha$ increases from $-\pi/2$ to $5\pi/4$. The $\alpha$ values are shown below the ellipses.

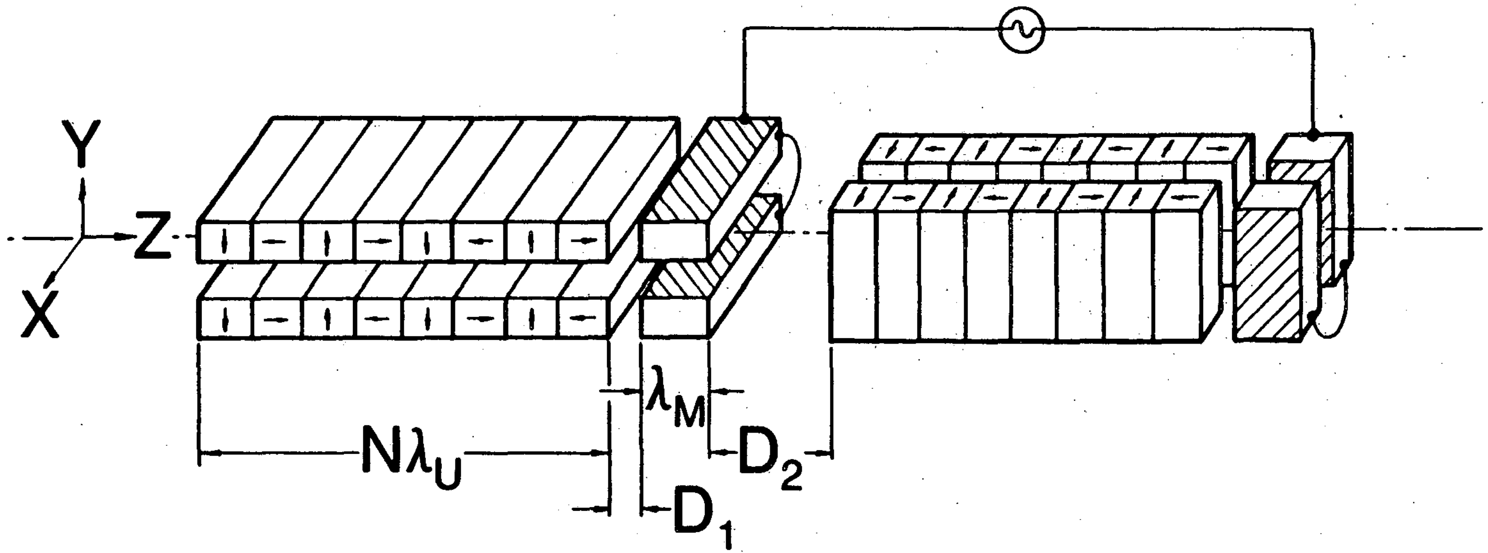


Figure 1

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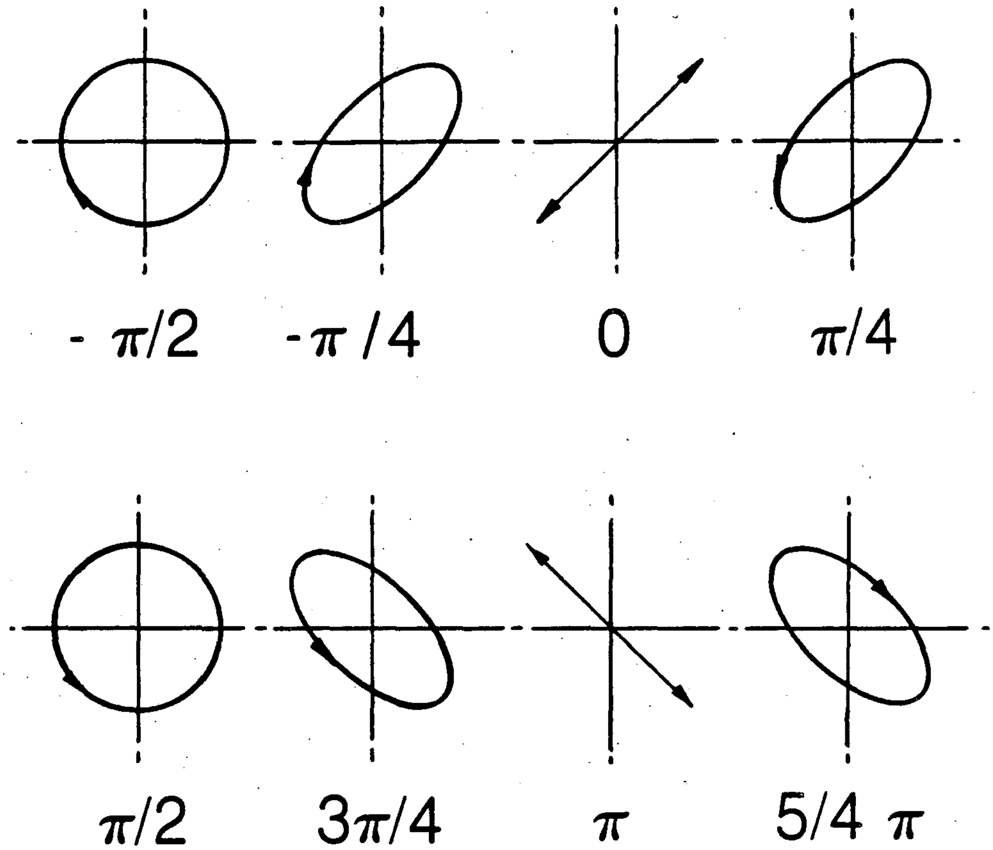


Figure 2

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