Two-Color Free-Electron Laser Operation

D.A. Jaroszynski, R. Prazeres, F. Glotin, and J.M. Ortega
Laboratoire pour l'Utilisation du Rayonnement Electromagnétique, Bâtiment 209d, Centre Universitaire Paris-Sud, 91405 Orsay Cedex, France
(Received 7 January 1994)

We present the first observation of two-color free-electron laser (FEL) operation using a single electron beam, single optical cavity, and a stepped undulator. The undulator is divided into two sections, each having different deflection parameters, K_1 and K_2, which set the resonance wavelengths for FEL oscillation at each of the nonharmonically related wavelengths. Each of the independently tunable optical pulses can have equal power, as high as half of that obtainable in single-wavelength FEL operation using both undulator sections. Presently the two-color FEL operates in the midinfrared spectral region.

PACS numbers: 41.60.Cr, 42.60.Fc

The free-electron laser (FEL) produces high intensity monochromatic optical radiation when a high energy relativistic electron beam passes through a periodic magnetic structure, called an undulator. The spontaneously produced brehmsstrahlung radiation is trapped in an optical cavity and amplified by a process of stimulated Compton backscattering [1,2]. The FEL is now well established as a unique source of intense tunable radiation presently spanning the far infrared to the ultraviolet and is utilized by many users from a large and varied scientific community.

The resonance wavelength, λ_0, of a FEL operating in the Compton regime is fixed by the undulator parameters and the energy of the electron beam, γmc^2, and is given by

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \quad (1)$$

where λ_u is the period of the undulator and K the peak deflection parameter [1]. The factor K includes the influence of the undulator magnetic field which varies on axis with the undulator gap. The wavelength of the FEL oscillator is shifted to wavelengths slightly longer than λ_0 because of energy conservation in the interaction process [1,2]. Tuning of the FEL wavelength can be achieved either by varying the electron beam energy or by varying the undulator K. The wavelength can be continuously varied by at least a factor of 2 by varying K. This latter method is the traditional method of tuning the wavelength of the FEL.

Conventionally only one fundamental resonance wavelength, given by Eq. (1), exists in the FEL because of the simple linear structure of the undulator. By operating the FEL using a two section undulator each with different deflection parameters, K_1 and K_2, respectively, we have been able to achieve laser action at two different wavelengths simultaneously. In this Letter we report the first operation of a two-color FEL hitherto not predicted theoretically.

In the "Collaboration pour un Laser Infra-rouge à Orsay," CLIO FEL [3], the electron pulses, derived from a 30–60 MeV, S-band, linear accelerator are short, about 10 ps, and contain approximately 5×10^9 particles. The undulator is constructed of two independently adjustable sections of $N_u = 24$ periods of $\lambda_u = 4$ cm giving a total of 48 periods [4]. Each section can have K independently varied from 0 to 2. The FEL CLIO produces on 8 μs train of optical micropulses, each separated by a maximum of 32 ns representing one cavity round-trip time. In the experiments discussed here we operate with a 32 ns interpulse spacing to be sure that the FEL operates on two colors simultaneously with only one optical pulse circulating in the cavity, however, the FEL will also operate with interpulse spacings down to 4 ns. Presently the range of operation of the FEL spans the wavelength range 2 to 17 μm and forms part of a user facility serving the needs of a large and varied user community requiring intense subpicosecond [5] to picosecond [3] optical radiation.

The stepped undulator of CLIO is of a conventional "Halbach" design [6] with independently adjustable gaps for each section as shown in Fig. 1. K_1 and K_2, the upstream and downstream undulator deflection parameters, respectively, can be independently adjusted between 0 and 2 [4]. The optical cavity of the laser is nearly concentric with a length of 4.8 m and a Rayleigh range of 1.2 m. The optical radiation is coupled out of the cavity using a ZnSe plate set close to Brewster's angle.

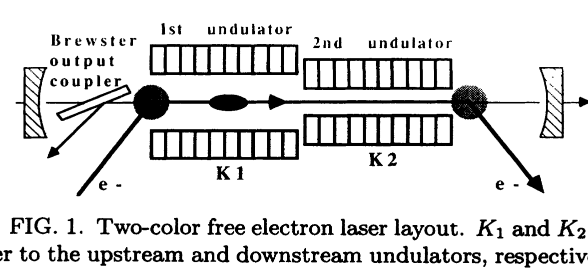

FIG. 1. Two-color free electron laser layout. K_1 and K_2 refer to the upstream and downstream undulators, respectively.

0031-9007/94/72(15)/2387(4)$06.00

The total output coupling fraction is approximately 6% over the entire wavelength range of CLIO and mirror absorption losses and diffraction losses are less than 2% at the shorter wavelength end of operation increasing at the wavelengths longer than 12 μm [3]. The output coupling plate has a small dispersion in frequency necessitating the readjustment of the cavity length to maintain synchronism between electrons and photons when changing wavelength, usually only necessary for wavelength changes greater than $\pm 25\%$.

The small signal gain per pass of CLIO is in the intermediate high or exponential gain range of 100% to 800% per pass because of the high peak current, 80 A [3]. As a result, the single pass gain for one undulator section operation, i.e., 24 periods only, is usually high enough for oscillation to occur to saturation over most of its wavelength range despite the high penalty on the gain imposed by the cubic dependence of the gain on the number of undulator periods. This intermediate high gain operation of CLIO is the main factor making it possible for the laser to operate at two frequencies simultaneously, a fact that is also supported by numerical simulations of two-color FEL operation that we have carried out and discuss later in this Letter.

Two-color operation has been observed presently at two electron energies, 40 and 50 MeV. However, we expect that two-color operation does not depend on the electron energy. To confirm that two-color FEL operation is indeed occurring we have measured the optical spectrum over a spectral range covering the two resonance wavelengths set by K_1 and K_2. Suitable long pass optical filters have been used to eliminate any higher harmonics present. For the purposes of our discussion we will refer to the centroid of laser wavelength associated with the upstream undulator as λ_1, and that associated with the downstream undulator as λ_2 and the wavelength difference as $\Delta\lambda = \lambda_1 - \lambda_2$. A large number of different steps $\Delta K = K_1 - K_2 = 0$ to ± 0.38 have been tested for two-color operation. For very small ΔK the two wavelengths are not completely separate because of the overlapping of the spectral widths of the individual lines. The largest ΔK where simultaneous two-color action has been observed corresponded to a gap difference of $\Delta g \approx 1.2$ mm. At 8 μm this corresponds to a difference in the wavelengths of $\Delta\lambda/\lambda \approx 15\%$. This upper limit in ΔK and $\Delta\lambda$ is due to the dispersion in the dielectric output coupler: different cavity lengths are necessary for synchronism between photons and electrons at the two wavelengths, respectively. Figure 2 shows typical measured spectra of two-color operation of the FEL evolving in time during the electron macropulse. In Fig. 2(a) the upstream undulator has a gap of 13 mm, $K_1 = 1.81$, and the downstream undulator a gap of 12 mm, $K_2 = 1.92$, giving a step in the undulator of 1 mm and a step in K of $\Delta K = 0.1$. The measured wavelength difference, $\Delta\lambda = 0.8$ μm, is slightly larger than that predicted using Eq. (1) giving $\Delta\lambda = 0.7$ μm. This is due to amplification

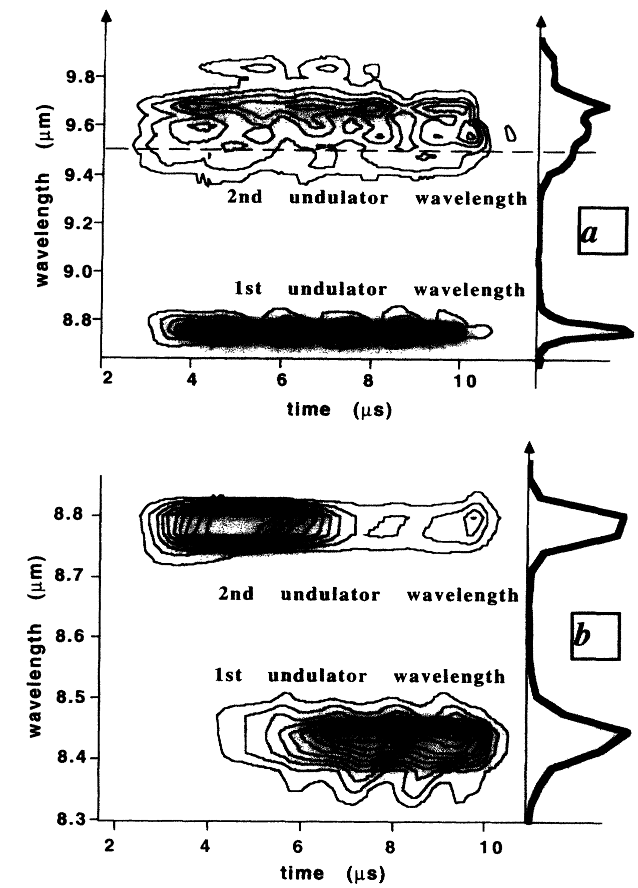

FIG. 2. Contour plots of measurements of the temporal evolution of spectra at 40 MeV. (a) $K_1 = 1.81$ and $K_2 = 1.92$ giving $\Delta\lambda = 0.8$ μm and peak powers of 3.3 and 7.6 MW, respectively. The dashed line represents the centroid of λ_2 for sole operation at λ_2. (b) $K_1 = 1.75$ and $K_2 = 1.81$ giving $\Delta\lambda = 0.35$ μm and peak powers of 8.4 and 7.0 MW, respectively. Integrated spectra are shown on the right hand side of the plot.

of λ_1 in the first undulator reducing the mean energy of the electrons entering the second undulator section, therefore increasing λ_2 slightly. The exact wavelength difference is difficult to predict exactly because both λ_1 and λ_2 depend on their respective powers in the cavity. The laser wavelength shifts toward longer wavelengths at higher powers because of the saturation process in the FEL [2]. The wavelength λ_2 depends on the mean energy of the electrons entering the second undulator section and therefore the power developing at λ_1. We have indeed observed a shift in λ_2 when there is laser action at λ_1. In Fig. 2(a) the dashed line represents the centroid of λ_2 when there is no laser action at λ_1, a condition obtained by changing the cavity length slightly to optimize synchronism for λ_2; this procedure is discussed in more detail below. The 2% difference between the centroids with and without laser action occurring at λ_1, as indicated in Fig. 2(a), is consistent with a shift in the resonance wavelength in the downstream undulator due to a reduction in the mean energy of $\Delta\gamma/\gamma \approx 1/4N_u$, i.e., $(\lambda_2' - \lambda_2)/\lambda_2 = 2\Delta\gamma/\gamma = 1/2N_u$ where N_u is the number of periods of a single undulator section, 24 in our case. We have also observed similar shifts of the wavelength λ_2 part way through the optical macropulse as a result of laser action building up at λ_1.

The shifts in energy due to laser action at λ_1 are also responsible for a reduction in the gain experienced at λ_2. This occurs as a result of the shift in the resonance wavelength. However, we usually observe a shift in wavelength accompanying the shift in energy to keep track of the resonance wavelength and therefore the optimum gain.

The total energy of the optical micropulses at both wavelengths is comparable with that obtained for single-color FEL lasing with $\Delta K = 0$. We calculate peak output powers of the order of 5–10 MW at each of the wavelengths. For the purposes of the calculation we have assumed an optical pulse length of 3 ps. It should be noted that a higher efficiency consistent with the shorter undulator, $N_u = 24$, is expected. However, as the gain for a single undulator is lower than for the full length undulator with $2N_u = 48$ periods it is not possible to obtain laser action to saturation within the electron macropulse duration at small cavity desynchronisms where the efficiency is maximum. The cavity desynchronism is set for optimum small signal gain rather than high power and high efficiency, for two-color operation, to obtain saturation before the end of the electron macropulse.

In addition to shifts in the wavelengths λ_1 and λ_2 there is an increase in the energy spread of electrons entering the second undulator section due to laser action in the first undulator section. Laser action at λ_1 induces an energy spread equal to the height of the potential well which itself is proportional to the square root of the electric field strength. This is of the order of $\delta\gamma/\gamma \approx 1/N_{u1}$ for CLIO at the onset of saturation. The small signal gain for λ_2 is reduced by a factor $1/[1 + 4N_{u2}^2(2\delta\gamma/\gamma)^2]$ leading to a reduction of two in the gain when the optical field at λ_1 begins to saturate. We explicitly denote the number of periods for the upstream and downstream undulators as $N_{u1} = 24$ and $N_{u2} = 24$, respectively. The optical field at λ_2 can be completely quenched when the gain falls below the losses. However, it is possible to control the saturation intensity at λ_1 by adjusting the optical cavity length slightly and therefore control the induced energy spread. An example of this interaction of laser action at the two wavelengths, observed in our measurements, is shown in Fig. 2(b) where the power at λ_2 is reduced after the intensity at λ_1 has built up to saturation.

We have observed that, by adjusting the optical cavity length by a small amount, a few wavelengths of the optical radiation, it is possible to adjust the relative intensities of the two wavelengths. In CLIO [3], as in other short pulse FELs [2], the range over which there is synchronism is of the order of a few optical radiation wavelengths long because of the combined influence of lethargy, slippage, and the electron pulse width [2]. The optimum length for synchronism between electrons and photons in the optical cavity is slightly different for the two wavelengths due to the dispersion of the ZnSe output coupling plate used in the experiment. At very large $\Delta\lambda$ the laser operates at only one of the two wavelengths, i.e., single color, because the range of cavity lengths over which the laser will oscillate does not overlap for λ_1 and λ_2, respectively. However, the power at either of the two wavelengths is comparable with that obtainable for $K_1 = K_2$.

To avoid the influence of the dispersive effect of the output coupler a very thin film coupler or a hole coupler could be used. The latter output coupling system is currently being installed on the CLIO FEL to avoid these problems.

To establish whether it is possible to predict two-color operation numerically we have preliminarily modified a numerical model, usually used to model single-wavelength operation [7], to include the change in the electron phase velocity in the second undulator section due to the different deflection strength K_2. The multiparticle model used for the investigations of the growth of the micropulses at the two wavelengths from spontaneous emission describes the interaction of the optical pulses with the electron pulses using the coupled Maxwell-Lorentz equations [2]. These nonlinear equations are solved in one dimension in the slowly varying amplitude approximation, to follow the evolution of the power to saturation [2]. The coupling with the Gaussian optical mode is modeled using a transverse filling factor. In the comparisons we make with our experiments we ignore the influence of transverse effects and concentrate on longitudinal dynamics only. The influence of inhomogeneous broadening of the gain spectrum is included in a realistic manner through an initial phase-space distribution of the electrons. The electron pulse shape used in the simulations is taken as having a triangular front edge and an exponential trailing edge with a full width at half maximum of 2.2 mm, consistent with measurements of the electron bunch shape on CLIO [3,8,9]. Figure 3 displays a typical numerical simulation of the evolution of two wavelengths for an electron energy of 40 MeV and K_1 and K_2 in the same range as those of the measurement of Fig. 2. Note that the start up time is arbitrary as it is determined by the level of the initial fields. Our model, however, does not include the dispersive influence of the output coupling plate in the optical cavity.

The gain of a stepped undulator exhibits interference effects similar to those occurring in an optical klystron, enhancing the gain at some frequencies and depressing the gain at other frequencies depending on ΔK [10–12]. The gain can be suppressed at either or both of the laser wavelengths, λ_1 and λ_2. This interference effect in the gain is largest for small ΔK values. In our measurements the intereference effects are observed as delayed saturation times due to a reduction in the small signal gain, i.e., at certain ΔK values the laser will start up slowly.

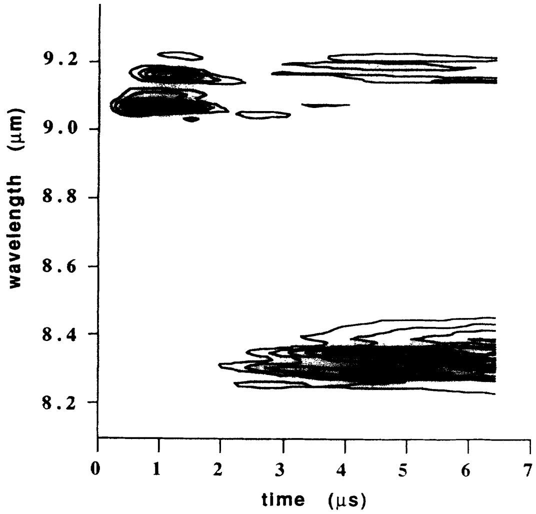

FIG. 3. Theoretical prediction of the temporal evolution of a typical spectrum. $K_1 = 1.77$, $K_2 = 1.90$, and an electron energy of 40 MeV.

Laser action occurs for both tapered ($K_1 < K_2$) and antitapered ($K_1 > K_2$) undulator configurations. In our observations the laser starts up either at λ_2, the wavelength set by the downstream undulator K_2, followed later by evolution at λ_1, or at both λ_1 and λ_2 simultaneously for two-color operation. This is possibly due to the prebunching of the electron beam as it arrives in the second undulator section due to laser action at λ_1. However, laser action is possible solely at λ_1 or λ_2 depending on the optical cavity length.

The two-color operation of the FEL is likely to greatly enhance its capabilities as a tool. Pump-probe experiments can now be done with an independent choice of the pump and probe wavelengths. Also, various nonlinear frequency mixing experiments can be considered to further extend the wavelength to longer wavelengths. Such experiments will be performed in the near future on CLIO. Other applications that may be possible are plasma-beam accelerators, selective two-color multilevel pumping in atomic, molecular, or solid state systems, the study of atomic Rydberg states, etc.

Experiments are also under way using autocorrelation and cross correlation techniques to establish whether the two colors are really simultaneous or whether laser action at each of the two wavelengths is constrained to different parts of the electron micropulse. From our numerical simulations it appears that the two colors overlap partially, although we have not included the dispersive dielectric output coupler in the simulations. We are also examining in detail, experimentally, the influence of the dispersive dielectric output coupler. In the first instance we will check whether two-color operation still occurs with hole output coupling.

It should be mentioned that an alternative method of producing two-color FEL operation has been proposed and never realized, but this includes two undulators and two different energy electron beams [13]. Our method, presented in this Letter, however, in contrast uses a single electron beam and a single optical cavity. The possibility of having cross polarized undulators where the first undulator magnetic field is perpendicular to the second so generating two differently polarized colors should be examined. As a user facility, it would then be very easy to separate the two colors using a polarizer. The possibilty of three or more color operation is also of interest.

[1] T. Marshall, *Free-Electron Lasers* (Macmillan Publishing Company, New York, 1985).
[2] W. Colson, in *Laser Handbook Vol. 6*, edited by W. Colson, C. Pellegrini, and A. Renieri (North-Holland, Amsterdam, 1990), p. 115.
[3] R. Prazeres *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 15 (1993).
[4] P. Bourgeois *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **304**, 150 (1991).
[5] F. Glotin *et al.*, Phys. Rev. Lett. **71**, 2587 (1993).
[6] K. Halbach, Nucl. Instrum. Methods **169**, 1 (1980).
[7] D. Jaroszynski *et al.*, Phys. Rev. Lett. **70**, 3412 (1993).
[8] R. Chaput *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 267 (1993).
[9] J. Ortega *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **285**, 97 (1989).
[10] C. Pidgeon *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **259**, 31 (1987).
[11] D. Jaroszynski *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **259**, 38 (1987).
[12] B. McNeil and W. Firth, Nucl. Instrum. Methods Phys. Res., Sect. A **259**, 240 (1987).
[13] H.A. Schwettman and T.I. Smith, J. Opt. Soc. Am. B **6**, 973 (1989).

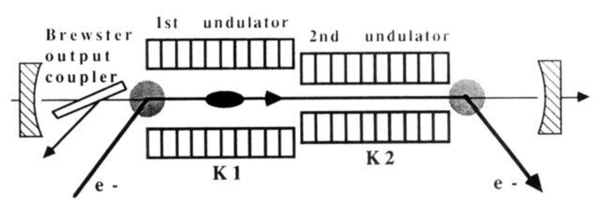

FIG. 1. Two-color free electron laser layout. K_1 and K_2 refer to the upstream and downstream undulators, respectively.