Eur. Phys. J. D 3, 87–93 (1998)

THE EUROPEAN PHYSICAL JOURNAL D

Two-colour operation of a Free-Electron Laser and applications in the mid-infrared

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Received: 4 November 1997 / Revised in final form: 31 March 1998 / Accepted: 10 April 1998

Abstract. The two-colour operation of a Free-Electron Laser (FEL) has been demonstrated with the "CLIO" infrared facility. A two section undulator allows the production of picosecond laser pulses at two different wavelengths λ_1 and λ_2 simultaneously, in a wavelength range from $\lambda = 5\,\mu$m to $\lambda = 18\,\mu$m, and with a wavelength separation of two colours of up to $\lambda_1 - \lambda_2 = 5\,\mu$m. The time overlap, between both colours, has been measured on a picosecond time scale and on a microsecond time scale. An initial pump-probe application experiment has been performed with the two colours: stimulated emission has been measured in a 3-level Quantum-Well system. This is the best demonstration of the stability and reliability of the two-colour laser operation.

PACS. 41.60.Cr Free-electron lasers – 42.60.Fc Modulation, tuning, and mode locking

1 Introduction

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

The resonance wavelength λ_R 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:

$$\gamma_R = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2) \tag{1}$$

where λ_u is the magnetic period of the undulator and $K = eB_0\lambda_u/2\pi m_0 c$ is the peak deflection parameter [1]. The factor K includes the influence of the undulator magnetic field B_0 on axis, which varies with the undulator gap. The wavelength of the FEL oscillator is shifted to a wavelength slightly longer than λ_R because of energy conservation in the interaction process [1]. Tuning of the FEL wavelength can be achieved either by varying the electron beam energy or by varying the undulator gap. The wavelength can be continuously varied by at least a factor of 2 by varying the undulator gap. This latter method is the traditional method of tuning the wavelength of the FEL. Conventionally only one fundamental resonance wavelength, given by equation (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 a different gap, g_1 and g_2 respectively, we have been able to achieve laser action at two different wavelengths simultaneously.

Amplification of the FEL is due to the exchange of energy from the electrons to the laser wave. The electrons are trapped in a ponderomotive potential associated with the beat wave of the laser and undulator fields, and lose energy as they traverse the undulator. The electron energy spread $\Delta\gamma/\gamma$, induced by this interaction, varies as the height of the ponderomotive potential, which is proportional to the square root of the laser field $|E|^{1/2}$, *i.e.* proportional to $I_L^{1/4}$, where I_L is the laser intensity. The small signal gain at start-up is dependent on the natural energy spread $\delta\gamma/\gamma = 1\%$ of the electron beam. However, on the other hand, the laser power at saturation does not depend on the natural energy spread $\delta\gamma/\gamma$, because the induced energy spread $\Delta\gamma/\gamma$ dominates at saturation. In the two-colour operation of the FEL, the laser action in the first undulator increases the energy spread approximately by the amount of $\Delta\gamma/\gamma$. For an excessive degradation of the electron energy spectrum, the gain in the second undulator section is reduced to the extent that simultaneous two colour operation is precluded. As a consequence, a large gain is required for the FEL in order to allow a two-colour operation with sufficient power and good stability. Significant FEL gain only occurs when the electron

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Table 1.

Electron beam:	
energy: γmc^2	30 to 60 MeV
peak current: i	100 A
90% emittance:	$150\,\pi$ mm mrad (normalized)
Time structure:	
macro-pulse:	$\Delta t = 10\,\mu$s
	repetition rate: 6.25 or 25 Hz
micro-pulse:	$\delta t = 8$ ps
	repetition rate: 4, 8, 16, 32 ns
Undulator (1^{st}): date of operation:	1992 to January 1995
nb. of periods:	$N = 24$ (for each undulator)
magnetic period:	$\lambda_u = 4$ cm
deflection:	$K = 0$ to 2
total length:	$L = 2N\lambda_u = 2$ m (for 2 undulators)
Undulator (2^{nd}): date of operation:	since January 1995
nb. of periods:	$N = 19$ (for each undulator)
magnetic period:	$\lambda_u = 5.04$ cm
deflection:	$K = 0$ to 2
total length:	$L = 2N\lambda_u = 2$ m (for 2 undulators)
Optical cavity:	
mirrors:	Silver coating on metalic mirrors
diameter:	$\Phi = 38$ mm
cavity length:	$L = 4.8$ m
Rayleigh length:	$Z_R = 1.2$ m
output coupling:	Brewster plate: from 1992 to 1994
	Hole coupling: since 1994
FEL:	
gain per pass:	$G \cong 100$ to 500% (for 2 undulators)
peak power:	$P = 100$ MW/1 ps (at maximum, for 1 colour)
spectral range:	$\lambda = 3$ to 50 μm

bunches and the laser photon pulse are well synchronised and overlap. This is achieved by adjusting the length of the optical cavity in order to match the cavity round trip time to the repetition rate of the electron bunches. The tuning of the cavity length influences the FEL gain, laser power at saturation, pulse length and wavelength spectrum. The two last parameters are linked by the Fourier condition because the laser pulses are close to the Fourier limit $\Delta\nu\Delta\tau \cong 1/2\pi$.

2 The CLIO free-electron laser

The "Collaboration pour un Laser Infrarouge à Orsay" (CLIO) facility is a mid-infrared FEL. The first laser oscillation was obtained in 1992 [2], and it has rapidly become a user facility for the infrared scientific community [3]. In the CLIO FEL, the electron pulses are derived from a 30-60 MeV S-band linear accelerator. They are 10 ps long, and contain approximately 5×10^9 electrons. The electron beam time structure consists of a $10\,\mu$s train repeated at 25 Hz. Each train contains micropulses of 10 ps, separated by 4, 8, 16 or 32 ns. The optical cavity of the laser is nearly concentric with a length of 4.8 m, corresponding to 32 ns round-trip time. The Rayleigh length of the optical cavity is $Z_R = 1.2$ m. In the experiments discussed here, we operate with 32 ns interpulse spacing to be certain that the FEL operates on two colours simultaneously with only one optical pulse circulating in the cavity. These characteristics are summarized in Table 1. The "small-signal gain" per pass of CLIO is in the intermediate high or exponential gain range of 100% to 500% per pass because of the relatively high peak current, 100 A [2]. Also, the total output coupling of the energy from the optical cavity is a few percent over the entire wavelength range of CLIO. As a result, the total gain, for one undulator section operation, 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 dependance 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-colour FEL operation [4]. Initially, the spectral range of the CLIO FEL spanned from 2 to 20 μm. In order to extend the spectral range of CLIO towards longer wavelengths, the configuration of the FEL has been changed slightly during the last years: the laser extraction system and the undulator have also been changed. The two colour operation of CLIO has been observed both with the initial and the new configurations.

Initially, the laser extraction coupling was performed by an intra-cavity ZnSe plate, set close to the Bewster angle. The operating wavelength was limited at $\lambda \cong 20$ μm because of the optical absorption in ZnSe at longer wavelengths. Nevertheless, for wavelength in the range $\lambda = 5$ to 15 μm, the net gain was sufficient to allow laser operation in the two-colour mode [4]. However, the dispersive properties of ZnSe did not allow the operation of the FEL with a wavelength difference $|\lambda_1 - \lambda_2| > 1$ μm, where λ_1 and λ_2 are the two colours produced by the FEL. Indeed, the output coupling plate had 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 $\Delta\lambda = \pm 25\%$. As a consequence, when the FEL operates in the two-colour mode, the optimum tuning length is slightly different for the two wavelengths. At large wavelength separation, $\lambda_1 - \lambda_2 > 1$ μm, the laser operates at only one of the two wavelengths, *i.e.* single colour because the range of cavity lengths over which the laser will oscillate does not overlap for λ_1 and λ_2 respectively. The gain obtained in two-colour mode is lower than in single colour mode, therefore, the tuning range of the optical cavity length is also shorter, and the wavelength tuning range is only about $\Delta\lambda \cong \pm 0.5$ μm $\equiv 5\%$. On the other hand, the dispersive properties of the cavity allow one to balance both colour intensities. Indeed, by adjusting the optical cavity length by a small amount, a few wavelengths of the optical radiation, it is possible to switch between the tuning ranges of λ_1 and of λ_2, and then to adjust the relative intensities of the two wavelengths.

In 1994, the intra-cavity plate has been removed and the laser extraction is done presently by a hole in the center of one mirror. This configuration is displayed in Figure 1. It is adapted to the mid-infrared operation because

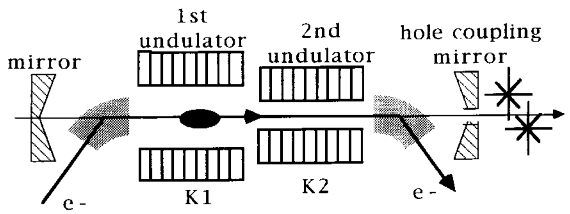


Fig. 1. Layout of the CLIO Free-Electron Laser in two-colour mode.

no absorption occurs in the cavity. However, the balance between the two colour intensities can not be achieved as before by tuning of the cavity with a dispersive effect. Nevertheless, we have shown that the hole coupling still allows two-colour operation, and the balance between colours is achieved by modification of the electron beam focusing, in the first or in the second undulator section. In this case, the wavelength difference $\lambda_1 - \lambda_2$ is not limited by dispersion, and we have measured a wavelength separation up to $\lambda_1 - \lambda_2 = 5$ μm, corresponding to $\Delta\lambda/\langle\lambda\rangle = 50\%$.

In the idea of extending the spectral range of CLIO toward longer wavelengths, the initial undulator has been replaced, in January 1995, by another one with a larger magnetic period [5]. These characteristics are displayed in Table 1. The FEL is now operating in a wavelength range from $\lambda = 5$ μm to 50 μm. Both the initial and present undulators have been constructed of two independantly adjustable sections, in order to allow two colour operation. In the two-colour mode, the total power of the optical macropulse at both wavelengths is about 5 MW for 1 ps laser micropulses, *i.e.* one tenth of the power obtained in single colour lasing. This lower efficiency is partialy due to the fact that, in order to compensate the lower gain obtained in two colour mode, the cavity desynchronism must be set for maximum small signal gain rather than high power and high efficiency.

3 Experimental analysis of the two-colour operation

3.1 Spectral analysis

For the purpose of our discussion, we will define the first undulator as the upstream one, with the associated gap g_1 and deflection parameter K_1 and the centroid of the laser wavelength λ_1; and we will define the second undulator as the downstream one, with the associated gap g_2 and deflection parameter K_2 and the centroid of the laser wavelength λ_2. Two colour operation has been observed at various electron energies, 50, 40 and 32 MeV. To confirm that two colour FEL operation is indeed occurring we have measured the optical spectrum over a spectral range covering the two resonance wavelengths of the two undulators set at gaps g_1 and g_2. Suitable long pass optical filters have been used to eliminate any higher order harmonic. A large number of different steps of undulator gaps $\Delta g = g_1 - g_2$ have been tested for two colour operation.

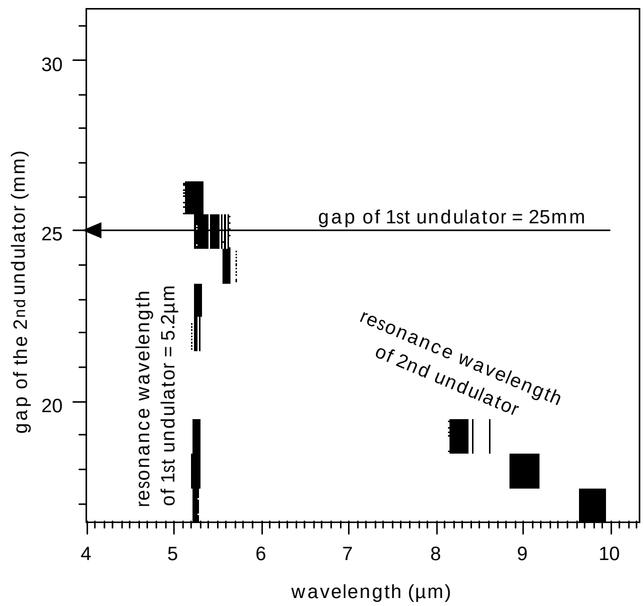


Fig. 2. Collection of spectra with a 50 MeV electron beam energy. Each spectrum has been done with a different gap for the 2nd undulator. The 1st undulator gap remains at $g_1 =$ 25 mm.

Figure 2 shows a collection of spectra, keeping the first undulator gap at $g_1 = 25$ mm and varying the second gap g_2 between 17 mm and 31 mm. The colour corresponding to the first undulator remains present at $\lambda = 5.2$ μm, while the other one varies between $\lambda = 5$ and 10 μm according to the gap g_2. This series of spectra have been measured while only varying the undulator gap g_2, and while maintaining the same electron beam parameters and cavity length. This demonstrates that the tuning of the two colours is fast and convenient. One particular spectrum, corresponding to the gap $g_2 = 24$ mm, needs to be commented: this spectrum exhibits only the second colour at $\lambda_2 = 5.6$ μm. The first colour at $\lambda_1 = 5.2$ μm is not present. This feature is always present in two-colour operation when the second undulator gap g_2 is slightly smaller than the first one: for example $g_1 = 25$ mm and $g_2 = 24$ mm as in Figure 2. The lack of spectral intensity at gaps 20 and 21 is only due to a transient unstability of the linac during the measurement, whereas the effect described here always appears in the same conditions. The lack of the first colour is due to a destructive interference between the spectral gain distributions of both colours. Indeed, the typical gain of an FEL shows an absorption of the radiation at wavelengths slightly shorter than resonance λ_R, and amplification of the radiation at wavelengths slightly larger than resonance. The particular configuration of gaps [25 mm, 24 mm] corresponds to an overlap of gain distributions at the wavelength $\lambda_1 = 5.2$ μm, which gives amplification in first undulator followed by absorption in the second one. As a result, the radiation at first colour, which is produced in the first undulator, is reabsorbed in the second one. Taking into account the theoretical width $\Delta\lambda = \lambda/N$ of

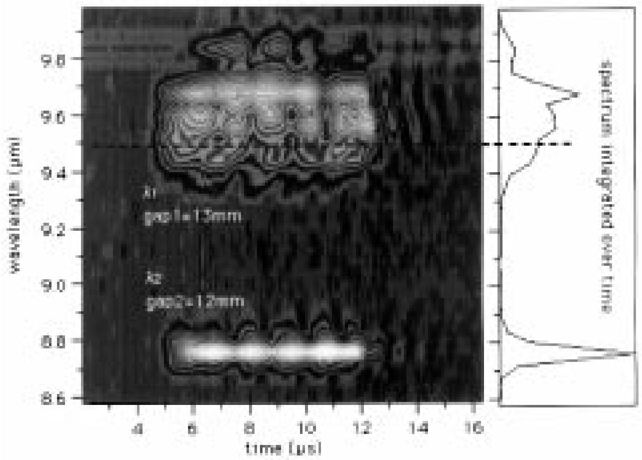


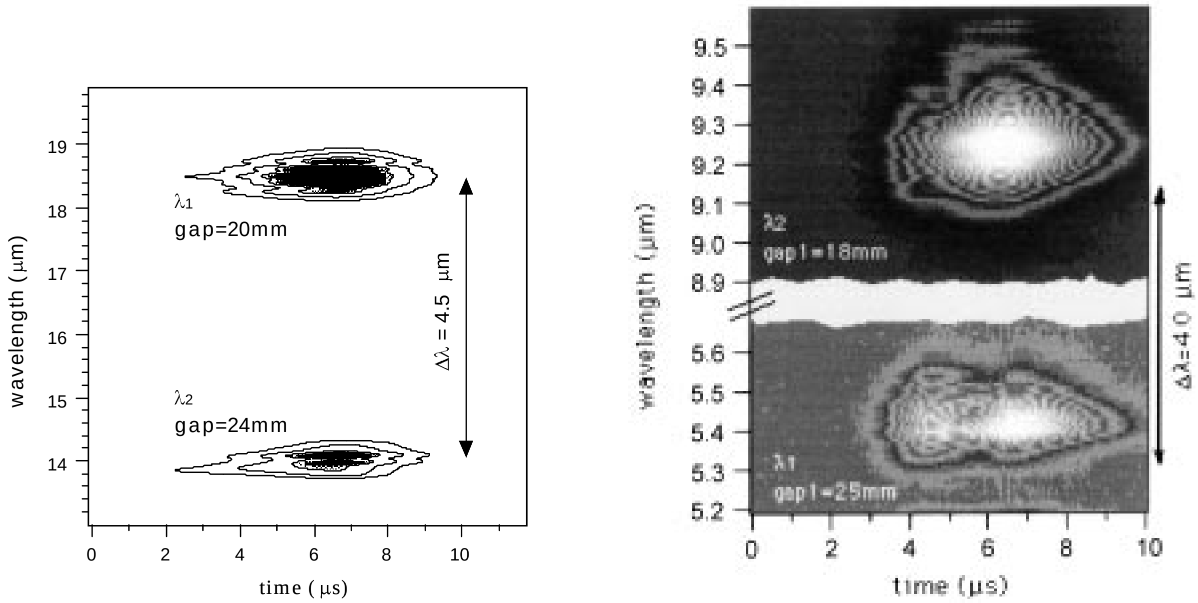
Fig. 3. Time evolution of the wavelength spectrum, during the electron beam macropulse duration of $10\,\mu$s. Measurement of Dec. 1993, with the ZnSe extraction plate and first undulator. The electron beam energy is 40 MeV, and the gaps respectively $g_1 = 13$ mm and $g_2 = 12$ mm.

the gain distribution for one undulator, this particular set of gaps occurs when $\lambda_2 = \lambda_1 + \lambda_1/N$, corresponding in our case to a difference $\lambda_2 - \lambda_1$ of 5% for $N = 19$ periods. The experimental spectrum in Figure 2 for the gap $g_2 = 24$ mm shows a separation $\lambda_2 - \lambda_1 = 5.6 - 5.2 = 0.4$ μm, corresponding to 7% which is close to the theory.

3.2 Time overlap at macropulse scale

The time overlap, *i.e.* longitudinal overlap, of both colours is an important condition to allow pump-probe application experiments. The Figure 3 displays an example of the time evolution of the spectrum, during the macropulse duration of $10\,\mu$s. This measurement has been carried out with the original configuration of the FEL: *i.e.* with the original undulator of $N = 24$ periods (per undulator section) of $\lambda_u = 4$ cm and with the Brewster plate output coupling. The electron beam energy is 40 MeV. The undulators are set respectively at the gap $g_1 = 13$ mm and $g_2 = 12$ mm, corresponding to $K_1 = 1.81$ and $K_2 = 1.92$, giving a step in the undulator gap 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 the value $\Delta\lambda = 0.7$ μm predicted by using equation (1). This is due to amplification 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 because both λ_1 and λ_2 depend on their respective powers in the cavity. The wavelength λ_2 depends on the mean energy of the electrons entering the second undulator section and therefore on the power developing at λ_1. We have indeed observed a shift in λ_2 when there is laser action at λ_1. In Figure 3 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 the synchronism for λ_2. This procedure uses the dispersive effect of the intracavity Brewster plate, as it is discussed above in Section 2. The 2% difference between the centroids with and without laser action occurring at λ_1, as indicated in Figure 3, is consistent with a shift in the resonance wavelength in the downstream undulator due to a reduction in the mean energy of $\Delta\gamma/\gamma \cong 1/4N$, *i.e.*, $\Delta\lambda_2/\lambda_2 = 2\Delta\gamma/\gamma = 1/2N$ where $N = 24$ is the number of periods of a single undulator section. 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 laser action at λ_1 in first undulator is also responsible for an increase of the electron energy spread, which broadens the laser linewidth at λ_2, as shown in Figure 3. The energy spread is equal to the height of the potential well, which itself is proportional to the square root of the laser electric field strength. This is of the order of $\delta\gamma/\gamma \cong 1/N$ at the onset of saturation (where N is the number of periods for each undulator). The small signal gain for λ_2 is reduced by a factor $1/\left[1 + 4N^2(2\delta\gamma/\gamma)^2\right]$ leading to a reduction by two in the gain when the optical field at λ_1 begins to saturate. The optical field at λ_2 can be completely quenched when the gain falls below the losses.

Figures 4a and 4b display two examples of the time evolution of the spectrum, with the new configuration of the CLIO FEL. These measurements have been done with the second undulator of $N = 19$ periods (per undulator) of $\lambda_u = 5.04$ cm and with the "Hole Coupling" extraction system. The electron beam energy is respectively 32 MeV for Figure 4a and 50 MeV for Figure 4b. The total energy of the optical macropulse at both colours is about 50 to 100 mW, which is one tenth of the power obtained in single colour lasing with $g_1 = g_2$. As shown in Figures 4a and 4b, the lower gain obtained for two colour operation allows laser saturation only during the last 3 or $5\,\mu$s of the $10\,\mu$s long electron macropulse. Let us point out that the saturation time exhibited in Figure 3, measured with the Brewster plate output coupling, is about $7\,\mu$s, which is twice the saturation time observed in Figures 4a and 4b, which were measured more recently, with the hole coupling extraction. The measurement of Figure 3 has been done two years prior to the measurements of Figures 4a and 4b. During this period, the undulator has been changed and the performances of the linear accelerator have certainly changed. We suppose that the last undulator is not as well compensated as the original one, and the electron beam trajectory through the undulator is not as straight as before. In any case, for Figures 3 and 4, both colours are simultaneous along the whole saturation time. This overlap does not occur automatically: we have sometimes observed a growth of λ_1 during the first microseconds of the macropulse, and followed by a growth of λ_2 with a simultaneous decrease of λ_1. This occurred more frequently with the original configuration, used for the measurement of Figure 3. The gain was larger than today, and it was sufficient to allow the growth of one colour during the first microseconds of the macropulse. Presently, the lower gain does not allow the observation of this effect as frequently as before.



(a) (b)

Fig. 4. (a) Time evolution of the wavelength spectrum, during the electron beam macropulse duration of 10 μs. Measurement of 1997, with the hole coupling and the second undulator. The electron beam energy is 32 MeV, and the gaps respectively $g_1 = 20$ mm and $g_2 = 24$ mm. (b) Time evolution of the wavelength spectrum, during the electron beam macropulse duration of 10 μs. Measurement of 1997, with the hole coupling and the second undulator. The electron beam energy is 50 MeV, and the gaps respectively $g_1 = 25$ mm and $g_2 = 18$ mm.

3.3 Time overlap on a micropulse time scale

The time overlap of both colours, on a micropulse time scale, is relevant to the understanding of the mechanism of two-colour generation. By focusing the laser in a Tellurium non-linear crystal, and measuring the spectrum of the emitted radiation, we have observed the sum-frequency component at $\lambda_{sum} = 1/(1/\lambda_1 + 1/\lambda_2)$. This spectrum is shown in Figure 5, which exhibits the two colours at $\lambda_1 = 8$ μm and $\lambda_2 = 9.7$ μm, with the sum-frequency component at $\lambda_{sum} = 4.4$ μm. We have chosen to work with not too separated wavelengths λ_1 and λ_2 in order to have a good efficiency of frequency mixing in the crystal. A measurement of the time delay between both colours, with sub-picosecond resolution, has been carried out with a Michelson interferometer followed by the Tellurium crystal and by a monochromator [6]. The Michelson divides the laser into two beams, delays one relatively to the other, and recombines both beams in the Te crystal. By choosing the appropriate wavelength and translating one Michelson arm length with a motorized mirror, we obtain either a standard autocorrelation profile for one or other colour, or a cross-correlation profile between the first colour pulse in one arm and the second colour pulse in the other arm. The monochromator is set at the sum-frequency λ_{sum} in order to allow detection only of the cross-correlation between the different colours λ_1 and λ_2. The detector used for detection of the sum frequency is InSb at 77 K. Because of the relatively long time response of this detector (about 10 μs), the measurements are time-averaged over the whole laser macropulse.

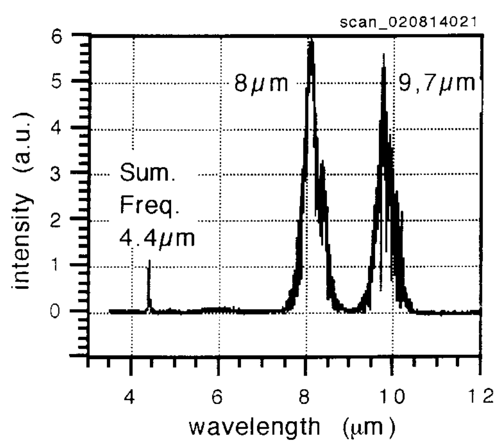


Fig. 5. Spectrum obtained by focusing the laser in a Tellurium crystal, showing the 2 colours and the sum frequency component λ_{sum}.

The Figures 6a and 6b respectively show two typical cross-correlation spectra, with the intensity of the sum-frequency as a function of the time delay introduced in the Michelson interferometer. In each figure, the top curve is

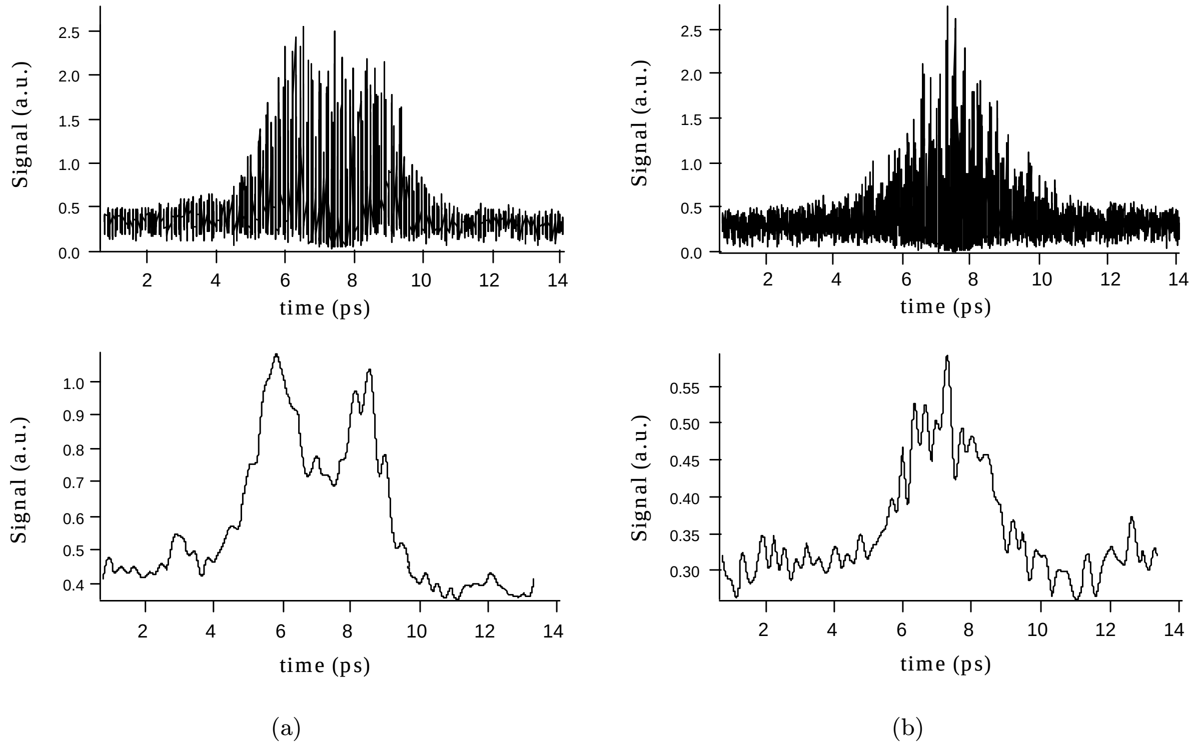


Fig. 6. (a) Cross-correlation spectrum between both colours, with *large* laser power: entire signal on the top curve, and smoothed on the bottom curve. (b) Cross-correlation spectrum between both colours, with *low* laser power: entire signal on the top curve, and smoothed on the bottom curve.

the entire spectrum, which exhibit the beating oscillations of the different wavelengths λ_1 and λ_2. The calculation of the Fourier transform of the interferometer spectrum exhibits peaks at frequencies $\nu_1 = c/\lambda_1$, $\nu_2 = c/\lambda_2$, $\nu_2 + \nu_1$ and $\nu_2 - \nu_1$. The lower curve is a numerical smoothing of the measurement. Figure 6a has been obtained at large laser power, and the Figure 6b at low laser power. Two peaks appear in the spectrum of Figure 6a, indicating that the two colours micropulses are not totally overlaping. One can note that due to the sum frequency and filtering process in our set-up, two very short pulses separated by δt in time would lead to two peaks spaced by $2\delta t$ in their cross-correlation spectrum. This is still a good approximation even if the pulse widths are comparable to the delay between the pulses. Here, Figure 6a is consistent with roughly Gaussian pulses separated by a delay equal to their FWHM, *i.e.* $\cong 1.2$ ps. This means there is overlap between these pulses, as is demonstrated more directly by the constant presence of a cross-correlation signal between the two peaks of this figure. Such a spectrum was the most commonly observed in our set of measurements. On the other hand, the low power curve of Figure 6b shows only one main pulse, and no clearly distinguishable substructure. This corresponds to a rather good overlap between both colours.

The non-overlap between the micropulses of both colours at large laser power is due to the electron energy spread induced by the laser power in the first undulator, which degrades the electron energy spectra to such an extent that simultaneous two- colour operation is precluded. As a consequence, the two colours do not fully overlap. In theory, the separation should be of the order of the slippage length $N(\lambda_1 + \lambda_2) \cong 1$ ps, which is in good agreement with the curve 6a. At low laser power, the full overlap is in principle allowed because the energy spread, induced by the laser action at λ_1 in the first undulator, is sufficiently small to allow amplification at λ_2 in the second undulator with the same part of the electron bunch. Let us point out that the picosecond time scale overlap is not important for pump/probe application experiments, since the two colours have to be separated and delayed independantly. Only the stability of the distance between the two colours is important. From our results, it is better than 1 ps.

These measurements have been carried-out under the same main operating conditions. Differences between them account for the many minor adjustments we made in order to keep a good amount of power for both colours. Optimisation is usually achieved by adjusting the cavity mirrors in position and angle, and the electron beam focus in the undulator. One must note that modification of the cavity length, which is used routinely in single colour operation to influence laser peak power and micropulse width [3] is here severely restricted -within a few microns- while attempting to preserve both colours. From our set of measurements, we conclude that there is almost always

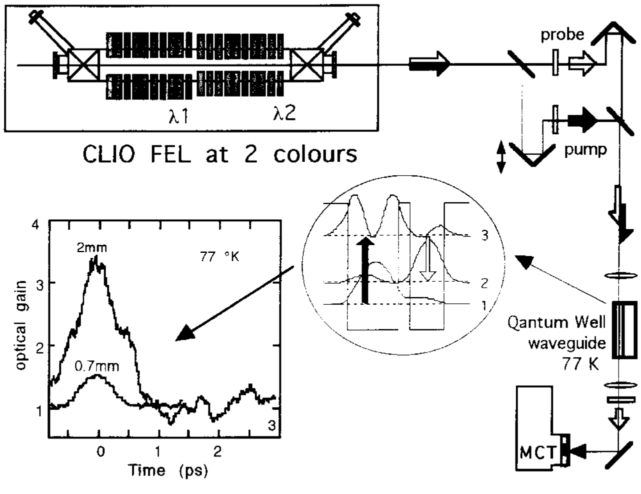


Fig. 7. Application experiment using the two colours for measurement of "stimulated emission" in a Quantum Well. Two sample have been tested, with a length of 0.7 mm and 2 mm.

an important temporal overlap of the two colours on a micropulse scale. Each colour seem to develop a 0.5−2 ps FWHM pulse, as in CLIO single colour operation mode when the optical cavity length approaches exact synchronism condition.

4 Application of the two-colour FEL

An initial application experiment has been performed with CLIO using the two-colours at $\lambda_1 = 9$ μm and $\lambda_2 = 12.5$ μm. Intersubband stimulated emission has been observed at 77 K in 3-level GaAs-AlGaAs semiconductor Quantum Wells embedded in an infrared waveguide [7]. Figure 7 displays the layout of the pump-probe experiment and the first set of curves, showing an optical gain of a factor of 2 to 3. The first colour, remaining at $\lambda_1 = 9$ μm, was used to bleach the intersubband absorption between the ground and second excited subband. Consequently, it creates a population inversion between the second and first excited subbands of the quantum wells. The second colour λ_2, scanned between 12 and 15 μm, was used as a probe for gain measurement through the sample. During a second set of experiments, with a higher quality sample, an optical gain of 100 to 1000 has been measured at the probe wavelength $\lambda_2 = 14$ μm [8]. Similar pump-probe experiments have been performed at room temperature in order to measure the lifetime of the excited subband states. A short life time $\cong 0.5$ ps has been measured in agreement with calculations accounting for electrons and polar optical phonons interactions [9]. These experiments demonstrate the stability of both colours during several hours, the flexibility of wavelength scanning, and also the good geometric alignment (in transverse plane) of both colours.

5 Conclusion

The large tuning range and versatility of the two-colour FEL has been demonstrated. A two-colour operation is possible with the CLIO FEL because of the two independent sections of the undulator, and because of the high gain produced by the large peak current of the electron beam. The two colours are produced in a large range of wavelengths, between $\lambda = 5$ μm and $\lambda = 20$ μm; and the wavelength ratio λ_1/λ_2 can be adjusted up to a factor of 2, for example $\lambda_1 = 5$ μm and $\lambda_2 = 10$ μm (as shown in Fig. 2). The average power is 50 to 100 mW and the peak power is about 10 MW in 1 ps, *i.e.* one tenth of the power in the single colour configuration. The time overlap between both colours has been demonstrated, with complete overlap on the macropulse time scale, and between 50 to 100% overlap on the micropulse time scale with a good temporal stability between both colours. The reliability of the FEL in the two colour configuration has been demonstrated by an application experiment, showing stimulated emission in a Quantum Well by optical pumping.

It should be mentioned that an alternative method of producing two-colour FEL operation has been proposed, but this includes two undulators and two different energy electron beams [10]. However, in contrast, our method presented here 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 colours should be examined. The possibility of three or more colour operation is also of interest. In the near future, some modifications of the linear accelerator will increase the gain in the wavelength range $\lambda = 20$ to 50 μm, and the optical beam line will be modified to allow a propagation in vacuum. This should allow us to extend the spectral range of the 2 colour operation up to $\lambda = 50$ μm.

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