Optical Frequency Multiplication by an Optical Klystron

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We report the first observation of the emission of coherent light by an electron beam bunched at 1.06 μm by a Nd-doped yttrium aluminum garnet laser focused into an optical klystron. An enhancement of 10^2 to 10^3 over its spontaneous emission level at 355 nm has been observed in these experiments performed at the ACO storage ring at Orsay.

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In the past few years much attention has been paid to the possibility of producing coherent light in the vacuum-ultraviolet ($\lambda < 2000$ Å) spectral range by use of free-electron sources.[1] One way is to realize a storage-ring free-electron laser[2] operating in this spectral range.[3] However, this will take some time to come about even with todays existing storage rings. Another possibility is to realize an up-frequency conversion of a high-power external laser focused into an optical klystron[4] or an undulator.[5] The external laser "bunches" the electron beam, i.e., makes a spatial partition of the electrons into microbunches separated by the laser wavelength, λ_L (Fig. 1). Therefore, in the Fourier analysis of the bunch density there appears a series of lines at the laser frequency and its harmonics. In the optical klystron (OK) configuration the external laser is focused into a first undulator (modulator) where it produces an energy modulation. This modulation is converted into a spatial modulation in the dispersive section (buncher) which is either a drift space or a long period of magnetic field. Then at wavelengths λ_L/n, where n is the harmonic number, light emission of the electrons passing through the second undulator (radiator) is enhanced by this coherent bunching and becomes proportional to the square of the number of electrons. This technique avoids the use of mirrors, as in the free-electron-laser case, to produce uv light. It should be efficient on most of the existing storage rings to produce light of wavelength between about 100 and 2000 Å by starting with a visible or uv, commercially available, laser. Although this process is often called "multiplication" or "up-conversion" it is different from the usual harmonic production since the coherent output power is taken from the electron energy and not from the pumping laser. Coherent emission by bunched beams (emission proportional to the square number of electrons) is a common fact in the centimeter and millimeter range of the electromagnetic spectrum. Recently, it has been observed with an undulator in the infrared.[6,7] However, no quantitative studies had been made yet. In this Letter we report the first observation of coherent light in the uv region produced by an OK with a high enhancement of the spontaneous emission.

The theory of the OK has been discussed by many authors,[8,9] as has the theory of harmonic production.[4,5] Let us only recall that, in the case of the OK, the ratio, R_n, of the coherent over the incoherent (spontaneous) emission, for the nth harmonic of the laser frequency and for a given laser power and within the bandwidth of the coherent emission, is proportional to

$$R_n \propto N I f_n^2, \tag{1}$$

where N is the number of periods of the radiator and I the ring current. f_n is the spontaneous-emission modulation rate, resulting from the interference of the two undulators constituting the OK, at wavelength λ_L/n. This interference is driven by the strength of the dispersive section and the energy spread of the electrons and

$$f_n \propto \exp\left[-\left(2\sqrt{2}\pi(N+N_d)\frac{\sigma_\gamma}{\gamma}n\right)^2\right], \tag{2}$$

where N_d is the number of wavelength of the yttrium aluminum garnet (YAG) laser passing over an electron in the dispersive section and characterizes

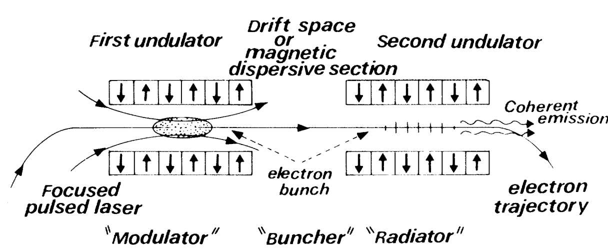

FIG. 1. Schematic principle of the experiment (see text).

TABLE I. Characteristics of the Nd:YAG laser.

Wavelength	1.06 μm
Beam dimensions at focal point (full width at half maximum)	400×700 μm^2
Pulse duration (full width at half maximum)	12 nsec
Peak power	15 MW
Repetition rate	20 Hz

TABLE II. Characteristics of the permanent-magnet optical klystron (Ref. 10).

Overall length	1.3 m
Undulator period	78 mm
Number of periods of each undulator	7
K value at 1.06 μm	2.0
Dispersive section field	0.55 T
N_d (Ref. 9)	74

the dispersive section strength[9] and σ_γ/γ is the relative energy dispersion of the beam. Thus this dispersion, which does vary greatly with I on the ACO storage ring, is a very crucial parameter.

The goal of this experiment was to demonstrate the feasibility of the harmonic production. Although there is no theoretical limitation in going into the vuv spectral range (by use of a higher electron energy), we chose to work in the visible part of the spectrum for convenience of detection. We used the 1.06-μm fundamental line of a pulsed Nd:YAG laser (Table I) focused into our optical klystron[10] (Table II) on the storage ring (Table III) working at 166 MeV, and looked at the third harmonic at 355 nm. At this energy, the modulation rate, f_3, is much smaller than one. This is due to the anomalous bunch lengthening which causes the energy spread to be much larger than the nominal energy spread at 166 MeV (1.4×10^{-4} for $I \lesssim 0.01$ mA). Also, there is an additional energy spread due to the interaction with the laser pulse, since the ring energy damping time is 180 msec at 166 MeV and the laser repetition rate was 20 Hz in our case.

The lower laser repetition rate (20 Hz) makes the long-time-average coherent emission very weak compared to the incoherent spontaneous emission whose repetition rate is 13.6 MHz. Thus the coherent power has to be measured on a fast time scale. Figure 2(a) shows the coherent-emission pulse together with the spontaneous-emission pulses for a weak amplification ratio and Fig. 2(b) for a strong ratio, so strong that the incoherent emission pulses do not appear on the record. The coherent emission pulse was sent to a boxcar averager in order to obtain an output signal proportional to the coherent power and integrated over many laser pulses.

The total angular divergence of the coherent emission has been found to be close to 1 mrad in good agreement with the diffraction limit $[\lambda\sqrt{2}/\pi(\sigma_x\sigma_y)^{1/2}$ where $\sigma_x \simeq \sigma_z \simeq 200$ μm are the bunch rms transverse dimensions]. The spectral width of the coherent emission is too small to be measured by our detection system. By using a monochromator of spectral resolution $\Delta\lambda \simeq 0.3$ Å we could only set an upper limit of 0.1 Å. Since the spontaneous emission is very broad ($\Delta\lambda \simeq 200$ Å), the measured values of R_3 depend linearly on the spectral resolution used and an absolute value can be set only by assumption of a given value for the coherent-emission spectral width. The value of R_3 (corresponding to a small solid angle), for $\Delta\lambda \simeq 0.7$ Å, has been measured for ring currents ranging from 0.1 to 10 mA. The modulation rate and the electron-bunch dimension have also been recorded in the same range of current (Fig. 3) in order to allow a comparison with the theory. The theoretical curve corresponding to formula (1) is also drawn on Fig. 3. It can be seen that the variations of R_3 with the ring current are qualitatively well explained by two opposite effects: The increase in the number of electrons and the strong decrease of the modulation rate ($f_3 \simeq 10^{-3}$ for $\sigma_\gamma/\gamma = 12\times10^{-4}$ at $I \simeq 10$ mA). The combination of these two factors produces the maximum observed at about 1 mA. The maximum measured value of R_3 is approximately 4×10^2 (for $\Delta\lambda = 0.7$ Å) although the theoretical

TABLE III. Characteristics of the ACO storage ring for this experiment.

Energy	166 MeV
Number of bunches	1
Repetition rate	13.6 MHz
Range of current	0.1–10 mA
Current lifetime	100–30 min
Energy spread	$(1.4\text{–}12)\times10^{-4}$

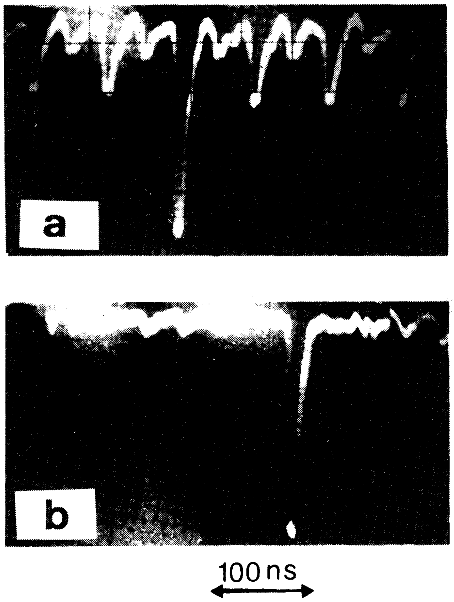

FIG. 2. Time structure of the optical klystron emission measured on the third harmonic of the fundamental line at 3550 Å. The pulse corresponding to a passage of the electron through the OK in coincidence with the laser is shown (a) for a weak amplification ratio ($R_3 \simeq 3$); (b) for a strong amplification ratio ($R_3 \gtrsim 100$).

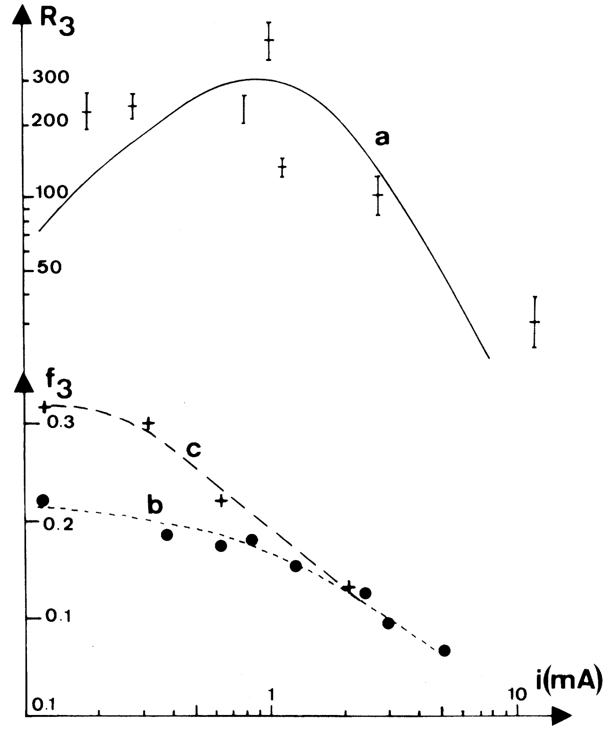

FIG. 3. Amplification ratio between the coherent and incoherent emission measured for $\Delta\lambda = 0.7$ Å and a solid angle of 0.2 mrad^2 (full line, theory; points with error bars, experiment) and modulation rate of the spontaneous emission measured with (curve b) and without (curve c) the laser, with respect to the ring current. Since the real spectral width of the coherent emission is less than 0.1 Å, the ordinate has to be multiplied at least by 7 to obtain the real value of this amplification ratio.

value is about 5 to 6 times more. We explained this effect by considering the pulse-to-pulse fluctuations of the coherent emission when recorded on a fast scope. These fluctuations are of the order of several units and do not appear on Fig. 3 where the signal is averaged over about 50 laser pulses. They might correspond to a time jitter between the electron and laser pulses of the order of a few nanoseconds considering the fact that the laser longitudinal pulse shape exhibits 2 to 3 peaks for a total duration of 12 nsec. We have also considered the effect of the lack of coherence of the laser ($\lambda^2/\Delta\lambda \simeq 15$ mm although the bunch length is ~ 300 mm). It seems to have no effect on the intensity of the coherent emission, but only on its spectral width. Let us point out that since the real spectral width of the coherent emission is less than 0.1 Å, as discussed above, the maximum measured value of R_3, within the coherent emission line, is at least 3×10^3.

The maximum number of coherent photons emitted per pulse is about 4×10^6 theoretically and 6×10^5 experimentally. This rather small number is due to various losses: (i) Because of the large energy dispersion of the ring at low energy, the maximum is reached at 1 mA of ring current where f_3^2 is only 10^{-2}. (ii) We worked at a lower laser power ($P_L \simeq 15$ MW); this accounts for a loss of a factor $\sim 10^2$ ($P_L \simeq 100$ MW and optimized dispersive section). (iii) We have a limited number of periods in the "radiator" section ($N = 7$). Thus a factor 10^6–10^7 is lost when we compare with an optimized klystron placed on a storage ring exhibiting no anomalous bunch lengthening. In our case the OK had been optimized for free-electron-laser studies[2,9,10] and the parameter N_d is too strong for this experiment. Moreover the energy of 166 MeV is very far from the nominal working energy of the ACO storage ring (540 MeV).

In summary, this work demonstrates for the first time the feasibility of the free-electron harmonic-generation experiment. This technique will be able to deliver 10^{10}–10^{12} photons/pulse when installed on modern storage rings working at their nominal energy. The spectral region covered should extend toward a few hundred angströms. Experiments in the vuv region are planned in the near future.

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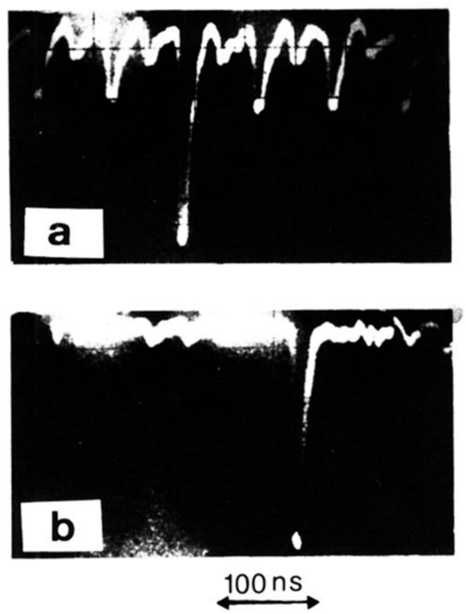

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