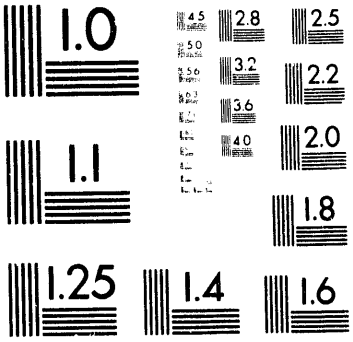
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Demonstration of Ultraviolet Lasing with a Low Energy Electron Beam*

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Abstract

We report on the design details of the first ultraviolet (UV) free-electron laser (FEL) oscillator driven by low-energy electrons from a radio-frequency linear accelerator. In our experiment we used a high-current, high brightness electon beam in combination with a wiggler of novel design to produce an FEL that lased at wavelengths from 369-380 nm using 45.9-45.2 MeV electrons. In addition we performed a proof-of principle experiment that demonstrated the first ever photolithography on a photoresist-coated silicon wafer using an FEL light source.

1. Introduction

Free-electron lasers have niches in regions of the optical spectrum where other sources are weak. Of particular interest are the infrared and the ultraviolet (UV) and soft x-ray regions[1-5]. Because of the unique challenges found in the UV, we have recently focused our attention there [6]. Limitations on electron beam emittance and current, and on wiggler design have in the past forced one to choose a high electron beam energy, such as in a storage ring, to produce an ultraviolet FEL. In recent years we have worked to improve each of the three component technologies of an FEL oscillator i.e. the electron beam the wiggler and the optics. The goal of this research has been to develop an FEL that will lase at the shortest ultraviolet wavelength possible using a 46 MeV electron beam as a driver. When one considers that previous UV FELs have used electron beams with energies at 350 MeV (VEPP-3, 240 nm) [7] to 800 MeV (Super-ACO, 350 nm) [8] and that the shortest wavelength ever achieved by an FEL with comparable energy to ours is 1.4 μm (Mark III, 38 MeV) [9], one concludes that our challenges were formidable. We believe that the developments described in this paper will have significant implications for short-wavelength FELs of the future.

The key development that has made our approach possible was the recent revolution in the design and construction of low-energy electron linear accelerators brought about by the introduction of radio-frequency photocathode electron-guns [10]. These photoinjectors have allowed the production and rapid acceleration of high-current beams without low-energy drift and bunching sections between the source and the accelerator [11]. This innovation has resulted in beams that have simultaneously both high peak-current ($I > 100$ A) and very low normalized emittance ($\varepsilon_n < 10\ \pi$ mm mrad) [12]. Such a low emittance beam allows the use of a wiggler with a much smaller transverse gap than was heretofore possible. A wiggler with a small gap can then have a small period and still have a high normalized vector potential (a_w). Lasing on a harmonic other than the fundamental is another consideration. Harmonic lasing increases the sensitivity of gain to energy spread. Fortunately electron beams produced by photoinjector linacs have a very small energy spread ($\sigma_E \ll 1\%$) which exhibits only a weak dependence on beam current [11]. The optical challenges are significant, not only because alignment tolerances

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become very tight, but also because of the necessity to suppress the fundamental during harmonic lasing. In this paper we describe the steps that lead to our success in third harmonic lasing from 369-380 nm using a 45.9-45.2 MeV range of electron energies.

2. Electron Beam

The 46-MeV APEX accelerator [13] used for these experiments has an rf photocathode source. The accelerator produces a 40-μs long macropulse-train of 8-15 ps (FWHM) electron micropulses at a 21.7 MHz rate. The use of solenoidal emittance-compensation [11] on the APEX photoinjector allows operation with a modest accelerating electric field of 25 MV/m at the cathode while still maintaining a low beam emittance. Without emittance compensation the APEX emittance would have been a factor of three higher according to Kim's theory [14] (see fig. 1). The low electric field on the cathode allowed us to use high quantum-efficiency multi-alkali cathodes without having field emission or arcing problems with the concomitant benefits of modest drive-laser power requirements and long macropulse capability. The ability to run long macropulses was critical to the successful UV lasing because of the long start-up time ($\approx$ 20 μs) of the FEL.

The key issue here for short wavelength lasing is the small emittance and its weak scaling with peak current. It is this scaling that gives sufficient gain for UV lasing because we can set the current to a high level while still maintaining small emittance. We have determined an empirical scaling relationship between rms normalized emittance (ε_n) and current for the APEX machine: $\varepsilon_n = (1 + e^{I/k})\ \pi$ mm mrad, where I is the peak current (between 50 and 340 A), and the constant k = 140 A. The emittance only begins to grow strongly for currents > 200 A. This is because of uncorrected transverse wakefield effects in the down-stream portion of the accelerator.

By using the measured relationship between emittance and current, along with the gain scaling relations from Dattoli et al. [14], we found that the optimum choice of current for lasing near 375 nm was between 100 and 200 A. Therefore, for the experiments described here, we chose an electron beam peak current of 135 A, which has a corresponding micropulse width of 8 ps FWHM. The energy spread of the electron beam was measured to be 0.24 % FWHM averaged over a 20 μs macropulse.

3. Wiggler

Our original plan for UV lasing involved the use of a pulsed microwiggler with a 5 mm period and a_w=0.7 [16]. Our efforts at lasing with this wiggler proved unsuccessful [17]. Fortunately our experience in working with the microwiggler and our success in transmitting the electron beam through a tube 1-mm in diameter and 300-mm long, led us to consider building a permanent magnet wiggler, with a short period and a very small gap, that would allow UV lasing on the 3rd harmonic.

The permanent magnet wiggler [18] that we used for lasing was a two-block-per-period Halbach design using samarium-cobalt magnets. The minimum wiggler period was achieved by having two blocks per period and the resulting wiggler period was 13.6 mm. To maximize a_w, the wiggler gap was chosen to be the minimum possible subject to constraints imposed by the sizes of the optical and electron beams. The diameter of the matched electron beam was approximately 0.4 mm and the diameter of the optical beam at the ends of the wiggler was 0.7 mm. To allow some room for steering and matching the beam into the wiggler we chose the gap to be 1.5 mm.

This gave an rms value of $a_w = 0.58$. The total number of wiggler periods was 73, and was constrained by the 1 m length of the available wiggler housing.

We chose an unusual arrangement for the wiggler magnets, i.e. with the magnetization vectors parallel and anti-parallel to the wiggler axis, so as to enhance the gain on the 3rd harmonic. Gain on the 3rd harmonic is derived from two different mechanisms. The fundamental component of a plane-polarized sinusoidal wiggler field generates gain on higher harmonics because the electron motion is not sinusoidal. In practice the wiggler field itself also has harmonic components. The 3rd harmonic component of the wiggler field generates 3rd harmonic gain by coupling with the 3rd harmonic component of the electron motion. These two gain mechanisms add or subtract depending on their relative phases [19]. In our case these mechanisms add. If we had chosen an arrangement of blocks where the magnetization vectors were perpendicular to the wiggler axis then the gain mechanisms would subtract. We estimate that our arrangement enhances the 3rd harmonic gain by approximately 20% over that of the alternative choice.

4. Optical Resonator

We used a near concentric linear resonator whose characteristics are summarized in table 1. The mirrors used were multi-layer dielectric (HfO and SiO) on a quartz substrate. Light was extracted from the resonator by transmissive out-coupling through the mirror substrate. The mirrors had to satisfy some unusual requirements as outlined below.

The mirrors should have high reflectivity in the UV near 370 nm for 3rd harmonic lasing, and low reflectivity at three-times 370 nm, i.e. 1110 nm, so as to suppress lasing on the fundamental. However we found it desirable to have high reflectivity near 1000 nm so that lasing on the fundamental would also be possible at a different electron beam energy from that required for 3rd harmonic lasing. We also required moderately high reflectance (~90%) at 527 nm, the wavelength of the photoinjector drive-laser. Injecting the drive-laser light into the FEL resonator and monitoring the multiple-pass ring-down facilitates setting the initial resonator length close to the spacing of sequential electron micropulses with an error of less than 100 μm. By lasing on the fundamental with an electron beam energy of 47 MeV the error in the cavity length could be reduced to less than 5 μm. Lowering the energy of the electrons to 45 MeV allowed lasing on the third harmonic while suppressing the fundamental.

We used two quarter-wave reflector stacks on each mirror: the upper one to reflect 360-380 nm light and the lower stack to reflect both 526.5 nm and 1 μm light.

5. Lasing

We used the FEL simulation code FELEX [20] to predict the performance of our experiment. The predicted gross gain was approximately 12%. Our strategy for setting the FEL cavity length worked and lasing was achieved on the fundamental at a wavelength near 990 nm using 47 MeV electrons. Then we lowered the electron beam energy to suppress the fundamental and lase on the 3rd harmonic. Lasing was achieved in the ultraviolet at wavelengths from 369 to 380 nm by varying the electron energy from 45.9 to 45.2 MeV. Care was taken to examine the optical spectra for the 2nd harmonic and fundamental during 3 rd harmonic lasing. The spectra on the fundamental and 2nd harmonic showed the characteristics of spontaneous emission with no evidence of lasing on these harmonics. This verified that the mirror design was successful in suppressing the fundamental.

Detailed measurements were made at 380 nm and are summarized in table 2. Figure 2 shows the optical signals as measured using a vacuum photo-diode. Lasing was typically achieved over the latter 50% of the electron beam macropulse i.e. the laser start-up time was approximately 20 μs. The start-up time for lasing as predicted by simulations was 18 μs. Note that the optical micropulse-pulse length was not measured directly but was inferred from simulations. Its length (6 ps) was less than the measured electron micropulse length (8ps) because of the low gain to loss ratio.

The measured spectral width during lasing was equal to the resolution of the optical spectrometer ($\Delta\lambda/\lambda \approx 4 \times 10^{-3}$). No sidebands were seen and none were predicted by simulation for a 20 μs long optical macropulse (40 μs electron macropulse). Simulations indicate that the onset of sidebands would have occurred if the electron macropulse were somewhat longer than 40 μs.

The major difficulty in the operation of the ultraviolet FEL involved the alignment of the electron beam in the wiggler and resonator. Because the optical beam and the electron beam waist radii were about 200 μm at the center of the wiggler, the small-signal gain was very sensitive to alignment. We found that moving the electron beam off the resonator axis by as little as 100 μm was sufficient to drive the gain below threshold. Tilting one of the cavity mirrors by 5 μrad from optimum was sufficient to stop the lasing. The short cavity detuning length was also a problem. The full detuning length was approximately 17 μm. The cavity length was measured to change by approximately 0.02 μm/s as a result of temperature changes in the FEL vault. A detailed measurement of the detuning curve was not possible because of drifts in the electron beam energy, optical cavity length and the mirror alignment. The lasing performance was very sensitive to the energy spread of the electron beam. An increase in energy spread by 0.1% was sufficient to drive the gain below threshold values. Visible lasing was also achieved on the 3rd harmonic near 510 nm with 39 MeV electrons.

As an adjunct to these experiments we performed a proof-of principle experiment to demonstration the first ever photolithography on a photoresist-coated silicon wafer using an FEL light source. These experiments indicated that there is nothing peculiar about an FEL in terms of peak power or pulse format that would prevent its use as a photolithographic light source. [21]

6. Conclusion

The experiments described here have validated the strategy of depending on improved emittance and harmonic lasing to achieve UV lasing with low energy electrons. We conclude that our simulation codes were reliable guides for predicting the performance of the FEL. The lack of robustness of the lasing indicates that the technology used here will require improvements before we can push to shorter wavelengths with low energy electrons. New wiggler options that will be available shortly include superconducting wigglers with iron pole-pieces [22] and pulsed electromagnet wigglers [23]. An improved photoinjector accelerator currently under test has produced electron beams whose emittance is 60% that of the APEX machine [24]. We believe that these developments are important precursors to FELs that will lase in the extreme ultraviolet and beyond.

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Figure captions:

1. Emittance (normalized, rms) versus peak current for the APEX accelerator. The APEX machine used solenoidal emittance compensation. The emittance predicted by Kim's theory for an uncompensated beam is shown for comparison.
2. Vacuum photo-diode signals while lasing at 380 nm: a) laser start-up regime showing a individual micropulse signals and net gain of 6±0.5 % per pass b) lasing macropulse envelope, c) cavity ring-down after electron beam shut-off, showing cavity losses of 6.5±0.5 % per pass.

Table captions:

1 FEL resonator specifications.
2 Performance of the FEL at 380 nm.

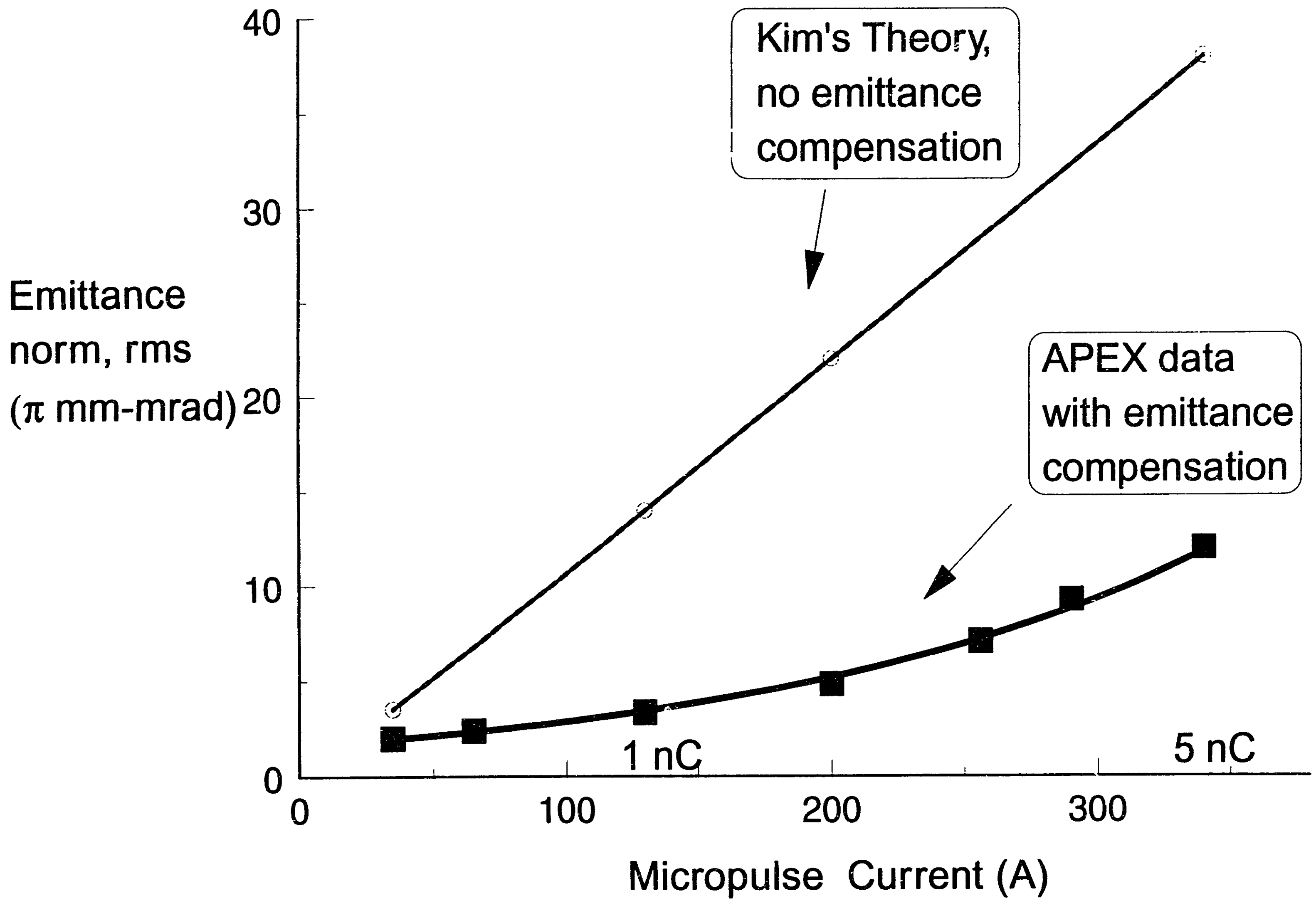
Table 1

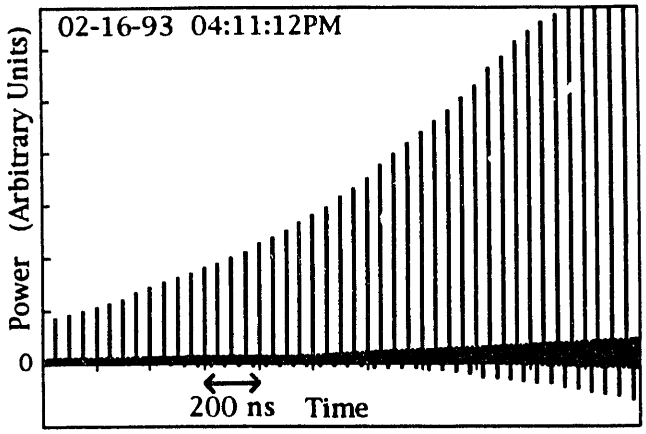
Cavity length (m)	6.9182
Mirror reflectance @ 380 nm(%)	96.3 %
Transmissive outcoupling (%)	1.1%
Mirror absorptance (%)	2.6%
Rayleigh Range	0.31 m
Mode size at waist	0.19 mm

Table : 2

Electrom beam energy (MeV)	45.2
Wavelength (nm)	380
Cavity losses per pass (%)	6.4±0.5
Small signal gain, gross (%)	12.4±1
Macropulse output power (W)	36±5
Macropulse length (μs)	20
Micropulse output power (kW)	270±70
Micropulse intracavity power (MW)	25±6
Micropulse length (ps)	6±1
Extraction efficiency (%)	0.04±0.01

EMITTANCE AT END OF LINAC

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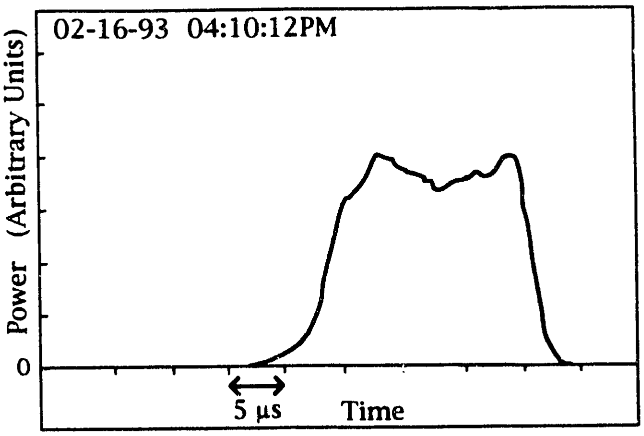
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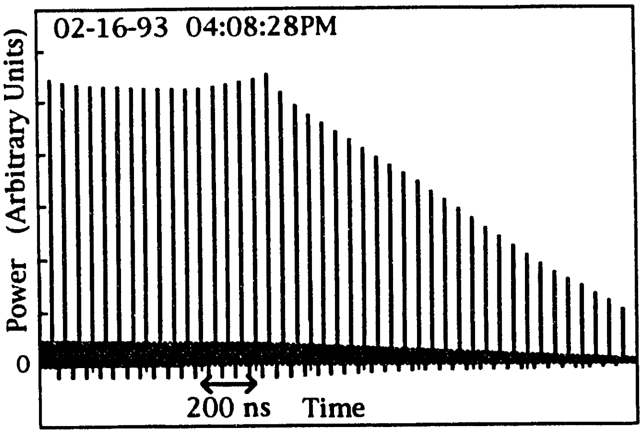

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