Second Harmonic FEL Oscillation

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We have produced and measured for the first time second harmonic oscillation in the infrared region by the high average power Jefferson Lab Infrared Free Electron Laser. The finite geometry and beam emittance allows sufficient gain for lasing to occur. We were able to lase at pulse rates up to 74.85 MHz and could produce over 4.5 watts average and 40 kW peak of IR power in a 40 nm FWHM bandwidth at 2925 nm. In agreement with predictions, the source preferentially lased in a TEM_{01} mode. We present results of initial source performance measurements and comparisons of with theory and simulation.

I. INTRODUCTION

We report the production, measurement, and initial characterization of harmonic operation using a high average power infrared free electron laser. Shorter wavelengths are possible in Free Electron Lasers (FEL) operating on a harmonic either as an oscillator in regions where mirrors are available, or in a "bootstrap" approach in an amplifier where lasing at one wavelength is used to increase the gain and amplification at higher orders. A number of groups have managed to operate an FEL oscillator on the third harmonic (three times the fundamental frequency) (*1*), or even the fifth (five times) (*2*) and one group has achieved bootstrapping an amplifier system by amplifying one wavelength to produce increased gain in a wiggler tuned for that wavelength's second harmonic (*3*). Second harmonic amplification has also been achieved in the microwave region in an over-moded waveguide utilizing a periodic position instability (*4*). This work reports a study of second harmonic laser oscillation at optical wavelengths in an open resonator in an anti-symmetric resonator mode, which leads to non-zero gain even for a perfectly aligned electron beam. This is equivalent to the periodic position interaction previously observed at microwave frequencies and in agreement with predictions made over 16 years earlier (*5*).

This work utilized Jefferson Lab's high average power infrared free electron laser, (IRFEL)which produces high-average-power coherent infrared (IR) light by combining continuous wave (cw) operation of superconducting radiofrequency (srf) accelerator cavities (producing a continuous train of electron pulses) with a technique that recovers the "waste" energy of the electron beam after it has been used for lasing *(6,7)*. The IRFEL has lased at continuous average powers up to 2.2 kW in a 74.85 MHz train of ~ picosecond pulses at 3.1 μm *(8)*. The accelerator and laser parameters utilized in this experiment are summarized in Table 1.

II. SECOND HARMONIC LASING - CONCEPT

The basic physics of FEL lasing is well understood (*9,10*). At a given optical frequency electrons of a particular energy are nearly synchronous with a pondermotive wave produced by the product of the optical wave and the wiggler field . Since the product **E•v** is slowly varying, energy can be transferred between the electrons and the optical wave and thereby growth of the optical power can occur. Coherence is established because these same actions produce longitudinal bunching of the electron beam at this wavelength.

There is zero gain of a plane wave on-axis for the even harmonics. This is most easily understood by looking at **E•v** for a general interaction between an optical mode and an electron.

For an arbitrary resonator mode interacting with an electron travelling down the wiggler the product **E•v** is given by

$$\mathbf{E} \bullet \mathbf{v} = E(x(t),y(t),z(t))\sin(k_W z(t) + kz(t) - \omega t + \phi_0) \quad (1)$$

where $k_W = 2\pi/\lambda_W$ is the wiggler wavenumber and k is the optical field wavenumber. It is quite easy to show that for a plane wave and constant velocity in the z direction, there is work done on the electron as a function of the initial phase ϕ_0 when the optical wavelength is given by $\lambda = \lambda_W (1 - \beta_z)/\beta_z$. This reduces to the familiar resonance wave equation when the longitudinal velocity is expressed in terms of the electron energy and the wiggler strength. It is also quite easy to see that, for constant z-velocity, that there will be no interaction at any of the harmonics because the phase reduces to ϕ_0.

For a planar wiggler the electron's z-velocity varies with the transverse velocity since the total velocity is constant. In a reference frame moving at the average electron velocity one finds that the electron executes a figure-8 trajectory. This means that there is an oscillation in the z-velocity at twice the wiggle frequency. When such an oscillation is added to z-motion in equation (1) it is clear that there will be coupling to all the harmonic of order $2h+1$ through the $\sin(2\omega t)$ term. The details of this dependence are shown in reference *(11)*. For a plane wave and a perfectly aligned electron beam, however, the coupling to the even harmonics is still zero.

To get coupling to the even harmonics it is necessary to break the symmetry of the system. There are two ways one might do this:

1. One can use an anti-symmetric resonator mode. In this case the wiggler motion produces a sinusoidal modulation at the wiggler frequency in the field amplitude seen by the electron. The electric field in equation [1] is then a sinusoidal function of the transverse coordinates. This field variation couples to the other motion to produce an interaction at

the even harmonics. Note that this can occur for even a perfectly aligned system as discussed in detail in (*5*). Also note that an offset electron beam in a symmetric mode will see the same effect.

2. One can misalign the electrons with respect to the optical axis. In this way the transverse velocity is biased and the gain spectrum has a non-zero value at the even harmonics. See reference *(12,13)*. Note that the electrons can couple to a resonator mode with even symmetry in this case.

Any real system will have a combination of these two phenomena and will therefore exhibit a mixture of even and odd symmetry resonator modes depending on the electron beam alignment.

Using the spontaneous emission formula *(14)* we can estimate the relative gain of the fundamental and second harmonic as a function of angle; these are shown in Figure 1. Previous, more accurate calculations(*16*) of the gain at the fundamental have arrived at values ranging from 60 to 100% small signal gain per pass under these conditions. It is evident that the maximum gain occurs off-axis in both the horizontal and vertical case (in our system the wiggle plane is vertical). It is understandable for the second harmonic gains to be highest in the vertical angle since the wiggler field is nominally unchanged in that direction whereas in the horizontal direction the field varies as $\cosh(2\pi x/\lambda_0)$ leading to dilution of the resonant condition.

We have also calculated the gain using the 3D nonlinear, polychromatic simulation code MEDUSA *(17,18)*. MEDUSA employs planar wiggler geometry and treats the electromagnetic field as a superposition of Gauss-Hermite modes using a source-dependent expansion. The field equations are integrated simultaneously with the 3D Lorentz force equations for an ensemble of electrons. No wiggler average is imposed on the orbit equations,. Using the IRFEL operating parameters for guidance we have calculated second harmonic small signal gain parametrically as a function of current and emittance. The results are shown in Figure 2a and 2b. For the best estimate value of the electron beam parameters, 60 A at 7.5 mm mrad normalized emittance, the predicted small signal gain in the TEM_{01} mode is 0.8%.

III. SECOND HARMONIC PRODUCTION – EXPERIMENTAL RESULTS

The experiment was performed by using two high reflectivity mirrors instead of the normal 10% out-coupling used for high average power production. The FEL is quite intolerant of transverse misalignment or longitudinal mismatch between the electron and optical beams. We typically align the optical cavity modes to better than 1 milliradian in angle (20 microradians of mirror tilt) and it will only lase over a cavity length change of 25 microns depending on conditions. Under the present conditions we set the laser to lase at the fundamental for 3.15 micron output. We then optimized the optical cavity alignment and electron beam steering and focussing. The detuning tolerance (cavity length over which it would lase) was 8.0405 m +0/-12 microns. Once this optimization had been achieved, we then lowered the energy by a factor of 1.37 from 48 to 35 MeV (rather than the ideal factor of 1.41, the 2nd harmonic wavelength was centered in the mirror reflectivity curves, minimizing the losses) and re-established the electron beam orbits, using our non-intercepting beam position monitors, to better than 100 microns of the original in the wiggler region. We also observed the steering and focus of the electron beam in the wiggler region using insertable viewers to verify proper setup; the electron beam orbit was always within 200 microns of the wiggler center. Our wiggler is essentially perfect as regards influencing electron trajectory and optical phase jitter for this wavelength. We scanned the cavity length and lasing commenced at the second harmonic. The lasing would occur over a range of cavity length of only 0.6 microns. Figure 3 shows the lasing spectrum at the second harmonic along with the spontaneous spectrum. By measuring the ring down time of the optical cavity we determined the cavity losses to be 0.62 % per pass. The small signal amplitude risetime was measured at low power and found to be 0.73%/pass corresponding to FEL gain of 1.35%. This gain value is also consistent with the ratio of fundamental to second harmonic gain one gets by taking the maximum derivative of the spontaneous spectrum in each case: 28:1. Given the uncertainty in the electron beam parameters and measured risetime of the light this is also fully consistent with the 0.8% small signal gain predicted by MEDUSA.

Despite the narrow region over which lasing would occur, the system was relatively stable and produced up to 4.5 W of average power from each end of the optical cavity. Using the known bunch length of the electron beam, the peak power outcoupled was ~ 40 kW in each picosecond pulse at 18.7 MHz.

The most interesting aspect of the lasing was the mode structure. When lasing on the fundamental the mode is Gaussian TEM_{00} with a $M^2<1.5$ (M is a measure of mode quality with 1 corresponding to a perfect Gaussian). In the case of the second harmonic we earlier demonstrated that gain on-axis is low compared to off-axis, thus favoring modes which have a null on axis and maximum intensity outside that region. The lowest order mode with these characteristics is a TEM_{01} mode, which has two vertical lobes and a null in the center. Figure 4 illustrates the TEM_{01} mode in second harmonic lasing.

We attempted to force the laser from a TEM_{01} into a TEM_{00} mode by putting a diffracting aperture into the cavity with a diameter chosen to match the fundamental mode but having large losses for higher order modes. We could not achieve lasing under these conditions on the second harmonic although lasing was essentially unaffected for the fundamental

V. SUMMARY

We have performed a study of laser gain in an open resonator FEL operating on the second harmonic. Under such conditions optical mode structures which are normally not supported in the free electron laser become favored and operate in a stable fashion although with tight tolerances. This is especially interesting in a laser where gain (and specific mode amplification) is over a pencil beam of very small transverse dimensions (~560 μm radius RMS by 110.7 cm long in the wiggler). We observed gains in the system that agree with simulation (MEDUSA), and measurements of the derivative of the spontaneous spectrum, detuning lengths, and ratios from calculated spontaneous spectra.

V. ACKNOWLEDGEMENT

The break-though performance of the IR Demo FEL was the result of a team effort as cited in (*6*) which we are happy to acknowledge. This work was supported by U.S. DOE Contract No. DE-AC05-84-ER40150, the Office of Naval Research, the Commonwealth of Virginia, and the Laser Processing Consortium. One of the authors (HPF) was supported by SAIC.

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Table 1: IRFEL system performance parameters. The IRFEL has a wide range of capabilities illustrated by the established figures in the middle column.

Accelerator and FEL Parameters		
Parameter	**Established capability**	**Second harmonic settings**
Kinetic energy (MeV)	28.0 – 48.0	35
Average current (mA)	4.8	2.25
Bunch charge (pC)	Up to 110	14 to 74 pC
Bunch length (rms) (femtosec)	300 - 500	~500
Peak current	Up to 60 A	Up to 60 A
Transverse emittance (rms) (mm-mrad)	7.5±1.5	7.5
Longitudinal emittance (rms) (keV-deg at 1497 MHz)	26±7	26
Pulse repetition frequency selectable settings (MHz)	18.7, x0.25, x0.5, x2, and x4	18.7, 74.85 MHz
Wiggler period (cm)	2.7	2.7
Number of periods	40.5	40.5
K_{rms}	0.98	0.98
Optical cavity length (m)	8.0105 stable daily to 2 μm	8.0105 stable daily to 2 μm
Output wavelength (μm)	1, 2.9-3.4, 4.8-5.3, 5.8-6.2	2.94

Figure 1: Relative peak gain estimated from derivative of the calculated spontaneous spectrum at the fundamental and second harmonic as a function of observer's angle off-axis in the horizontal and vertical planes. Spontaneous emission spectra were calculated using SRW(*15*).

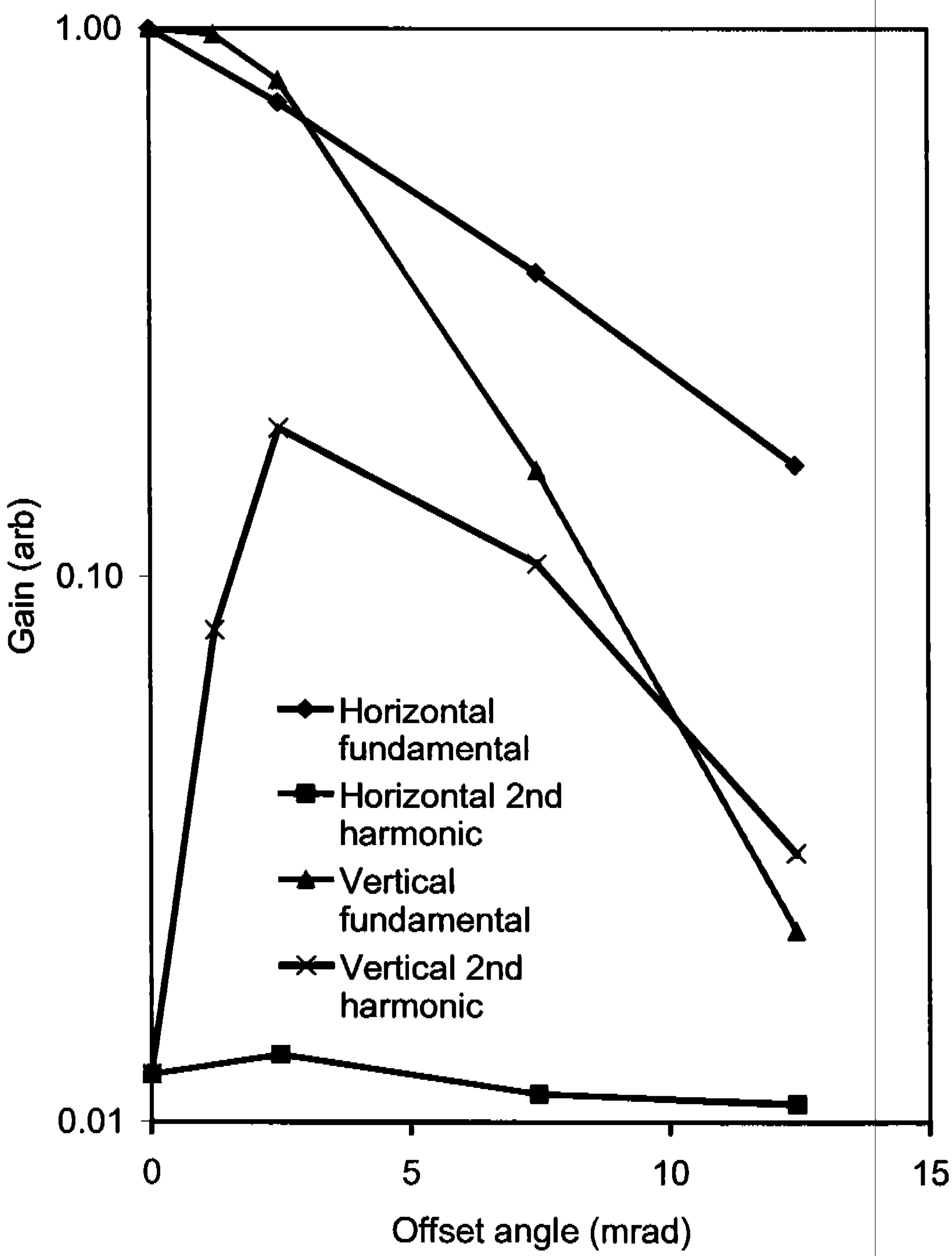
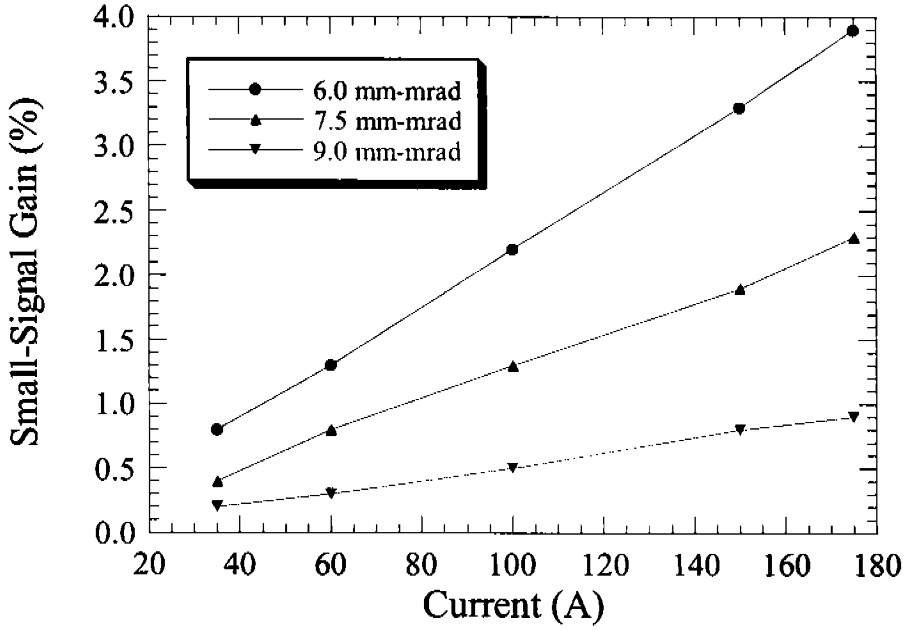


Figure 2. FEL Gain calculated by MEDUSA a) as a function of current b)as a function of normalized beam emittance.



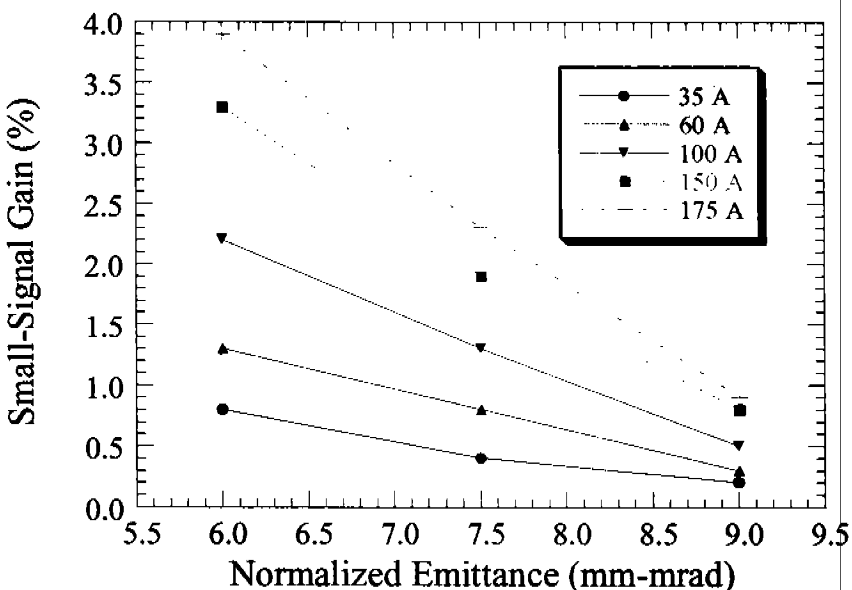


Figure 3: Second harmonic lasing spectrum displayed with the spontaneous spectrum under the same conditions. The vertical scales are arbitrary. The maximum average lasing power was 3 watts. The predicted spontaneous power is on the order of nanowatts but was not measured.

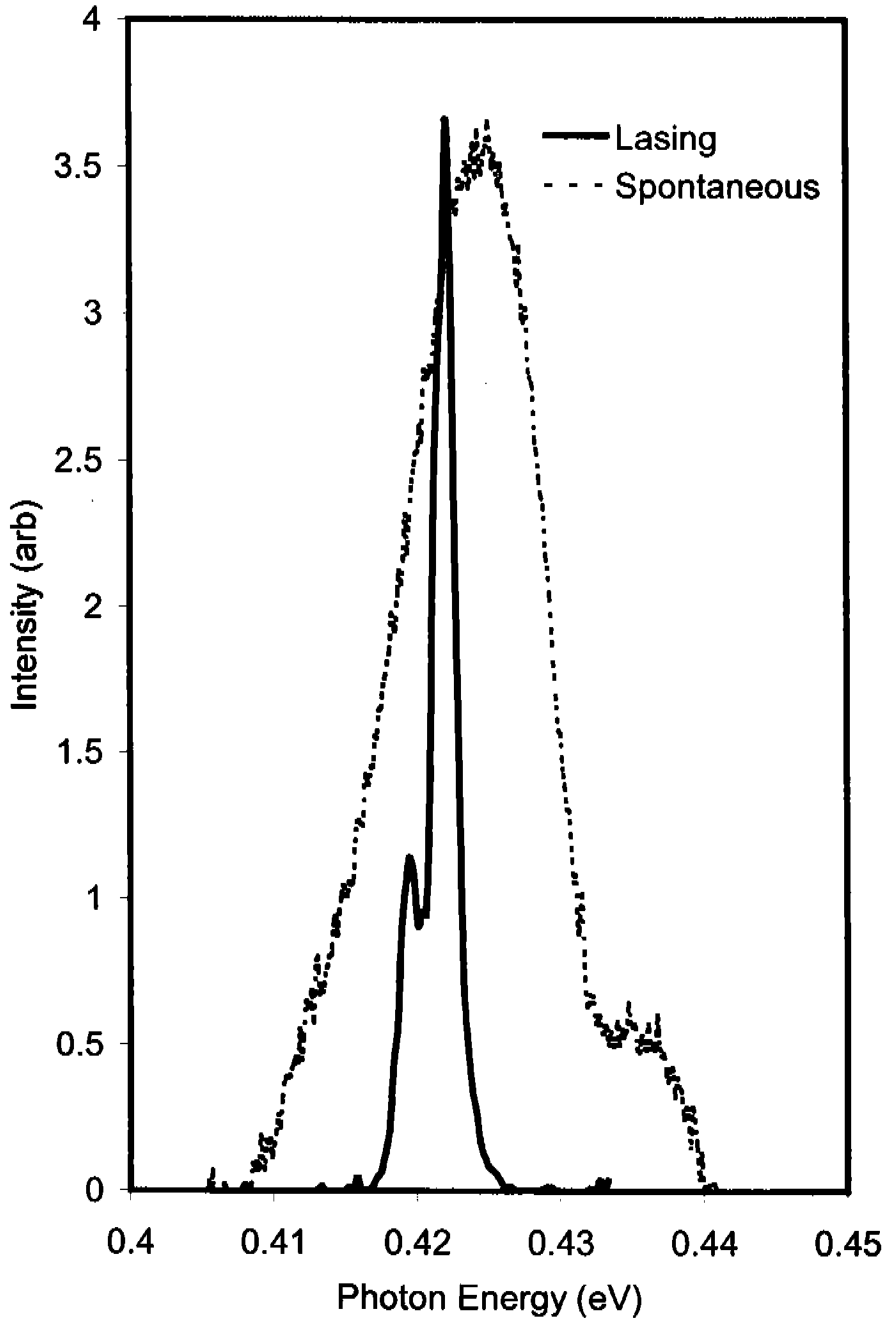


Figure 4: a) Infrared impinging on the optical beam dump showing the second harmonic TEM_{01} mode. The image is tilted due to relative misalignments in the system with perhaps additional contributions from coupling due to misalignment in our optical collimator.