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 a free electron laser. Although such lasing is ideally forbidden, since the gain of a plane wave is zero on axis for an electron beam perfectly aligned with a wiggler, a transverse mode antisymmetry allows sufficient gain in this experiment for lasing to occur. We lased at pulse rates up to 74.85 MHz and could produce over 4.5 W 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.

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I. Introduction.—One method of getting shorter wavelengths from a free electron laser (FEL) is to operate the laser 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. Although there are limitations to extending this approach, a number of groups have managed to operate an FEL oscillator on the third harmonic (3 times the fundamental frequency) [1], or even the fifth (5 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]. Even harmonic amplification has also been achieved in the microwave region in an overmoded waveguide utilizing a periodic position instability [4]. The work reported here pursues a physics study of second harmonic laser oscillation at optical wavelengths in a resonator under conditions which are forbidden for ideal systems but permitted here due to an antisymmetric resonator mode, which leads to nonzero gain even for an aligned electron beam. This is in agreement with predictions made over 16 years earlier [5].

This work utilized Jefferson Lab's high average power infrared free electron laser (IRFEL). The IRFEL produces high-average-power coherent infrared (IR) light by combining continuous wave (cw) operation of superconducting radiofrequency 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. The IRFEL has lased at continuous average powers up to 1.72 kW in a 74.85 MHz train of ~picosecond pulses at 3.1 μm wavelength [6]. The design of the machine, patterned after the CEBAF accelerator, a unique multi-GeV cw electron accelerator developed for fundamental nuclear physics research, is discussed in more detail elsewhere [7]. The accelerator and laser parameters are summarized in Table I.

II. Second harmonic lasing concept.—The basic physics of FEL lasing is well understood [8,9]. At a given optical frequency electrons of a particular energy are nearly synchronous with a ponderomotive wave produced by the product of the optical wave and the wiggler field (typically a linearly polarized sinusoidal field produced by a series of electro- or permanent magnets). Since the product $\mathbf{E} \cdot \mathbf{v}$ 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. Gain exists on axis for all odd harmonics and, if gain is sufficient to overcome losses *and lasing at the higher-gain fundamental frequency can be suppressed,* then lasing at these harmonics can occur. In previous work we achieved lasing at the fifth harmonic only by having the mirrors highly transmissive at the fundamental and third harmonic. For even harmonics the emission along the axis for a perfectly aligned electron is zero but emission off-axis can occur due to coupling to an electron beam's finite extent and betatron motion in the wiggler [5].

Without on-axis emission at the second harmonic, where can the gain come from? This is most easily examined by looking at a detailed form of $\mathbf{E} \cdot \mathbf{v}$ for a general interaction between an optical mode and an electron. For an arbitrary resonator mode interacting with an electron traveling down the wiggler the product $\mathbf{E} \cdot \mathbf{v}$ is given by

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

where $k_W = 2\pi/\lambda_W$ is the wiggler wave number and k is the optical field wave number. 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, there will be no interaction at any of the harmonics because the argument of the sin reduces to ϕ_0. This is true for a helical wiggler where the z velocity is constant.

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-eight

TABLE I. IRFEL system performance parameters: The IRFEL has a wide range of capabilities illustrated by the established figures in the middle column. The specific parameters for the x-ray experiments are shown in the third column.

Parameter	Accelerator and FEL parameters 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) (fs)	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, ×0.25, ×0.5, ×2, and ×4	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	8.0105
Output wavelength (μm)	Stable daily to 2 μm 1, 2.9–3.4, 4.8–5.3, 5.8–6.2	Stable daily to 2 μm 2.94

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 Eq. (1) it is clear that there will be coupling to all the harmonic of order $2h + 1$ through the $\sin(2\omega t)$ term within the argument of the sin. The details of this dependence are shown in Ref. [5]. 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 antisymmetric 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 Eq. (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 [10]. (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 nonzero value at the even harmonics. This is quite well described in Ref. [5]. 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.

As an example of the second mode of second harmonic gain, we calculated the on-axis spontaneous spectrum of the JLab FEL (Fig. 1). Only a small amount of second harmonic light is predicted, 4×10^{-8} photons/s per 0.1% bandwidth. When the same spontaneous spectrum is calculated 1.25 mrad off axis, the second harmonic intensity is enhanced by a factor of 20 while the fundamental drops only 20%. As shown by Madey [11] and experimentally confirmed by Elias [12] gain of the FEL is proportional to the derivative of the spontaneous field with respect to frequency. [See [5] for comments about the validity of the Madey theorem off-axis.] Previously, more accurate calculations [13] of the gain at the fundamental have arrived at values ranging from 60% to 100% small signal gain per pass under these conditions. Using such calculations

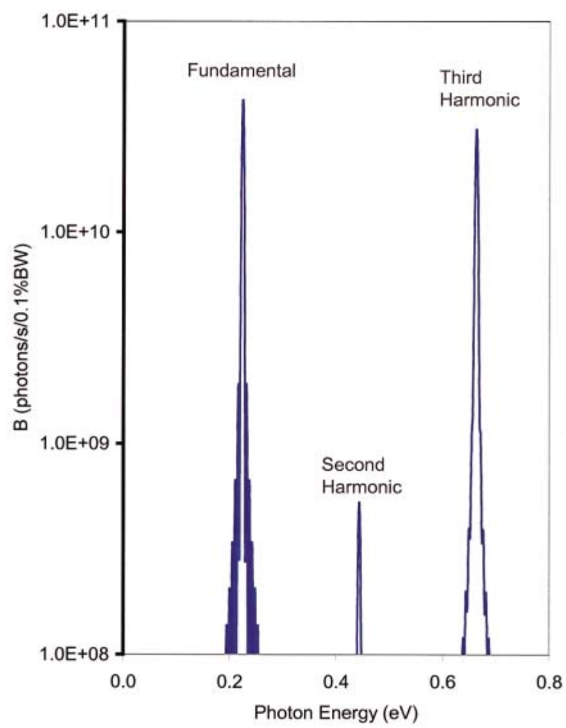

FIG. 1 (color). Calculated spontaneous spectrum of electron beam passing through the JLab wiggler when observing on axis. Calculations performed with SRW [15].

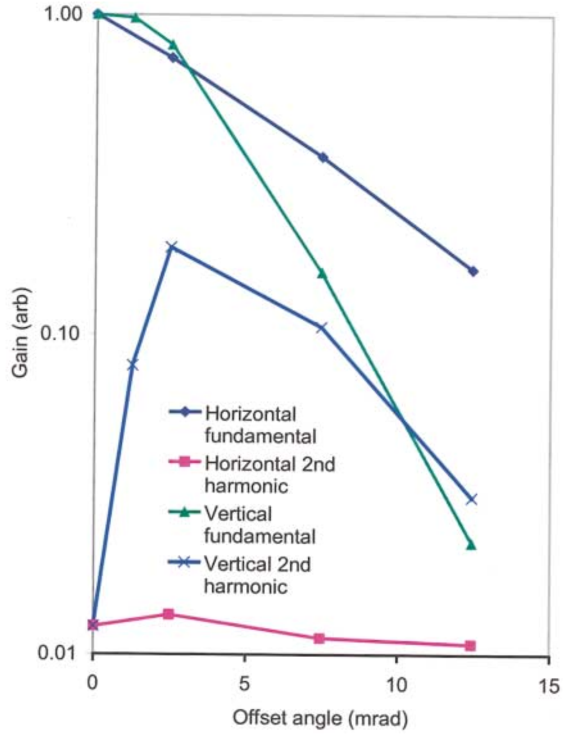

FIG. 2 (color). Relative peak gain estimated from derivative of the calculated spontaneous spectrum at the fundamental and second harmonic as a function of observer's angle off-axis in the horizontal and vertical planes.

we can estimate the relative gain of the fundamental and second harmonic as a function of angle; these are shown in Fig. 2. It is evident that the maximum gain occurs off-axis in both the horizontal and vertical cases (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.

III. Second harmonic production: experimental results.—The experiment was performed by using two mirrors of very high reflectivity 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 have to align the optical cavity modes to better than 1 mrad in angle (20 μrad of mirror tilt) and it will lase only over a cavity length change of 25 μm depending on conditions. Under the present conditions we set the laser to lase at the fundamental for 3.15 μm output. We then optimized the optical cavity alignment and electron beam steering and focusing. The detuning tolerance (cavity length over which it would lase) was 8.0405 m $^{+0}_{-12}$ μm. 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 second harmonic wavelength was then centered in the mirror reflectivity curves, minimizing the losses.) We reestablished the electron beam orbits, using our nonintercepting beam position monitors, to better than 100 μm 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 μm of the wiggler center. Our wiggler is essentially perfect as regards influencing electron trajectory and optical phase jitter for this wavelength. Under these conditions the mirrors are not highly reflective at the new fundamental wavelength of 6 μm but are highly reflective in the 3 μm region where the second harmonic is located. We scanned the cavity length and lasing commenced at the second harmonic. The lasing would occur only over a range cavity length of 0.6 μm. 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 gain was measured using the rise time at low power and found to be 0.73% per pass corresponding to FEL gain of 1.35%. This gain value is consistent with both the ratio of the fundamental to

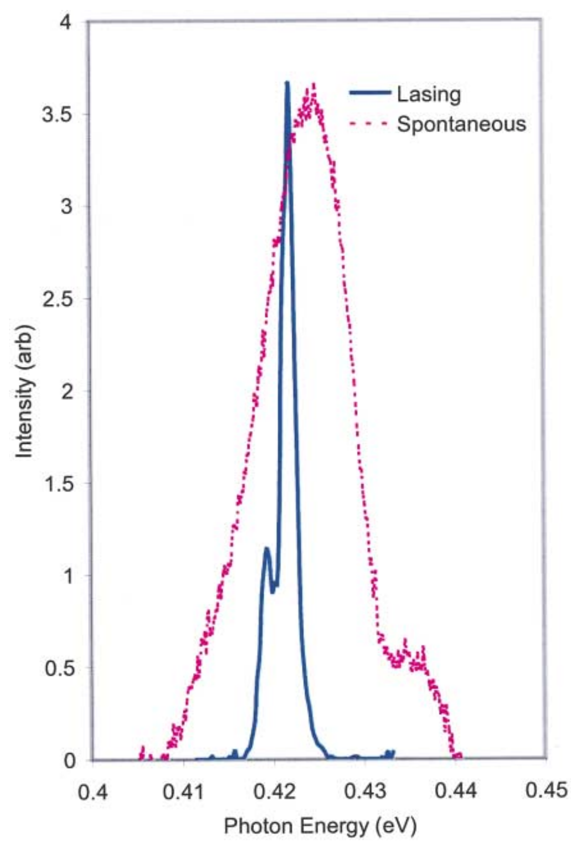

FIG. 3 (color). Second harmonic lasing spectrum displayed with the spontaneous spectrum under the same conditions. The vertical scales are arbitrary. The maximum average lasing power was 3 W. The predicted spontaneous power is on the order of nanowatts but was not measured.

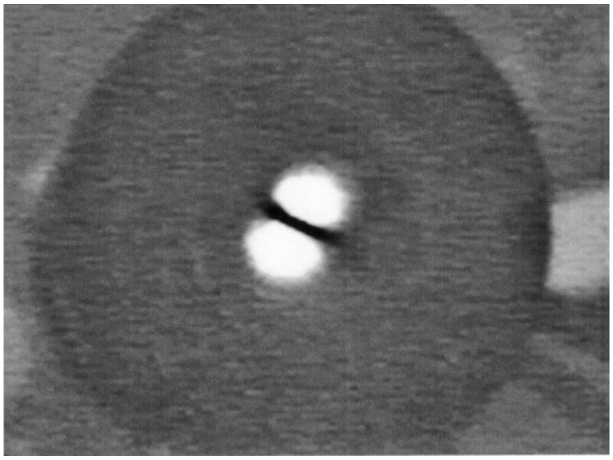

FIG. 4. Infrared impinging on the optical beam dump showing the second harmonic TEM_{01} mode. The image is tilted due to relative misalignments in the system with perhaps additional contributions from coupling due to misalignment in our optical collimator.

second harmonic length detuning curve widths (40:1) and the ratio of the maximum derivatives of the spontaneous spectra (28:1). 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 $M^2 < 1.5$ (M is a measure of mode quality with 1 corresponding to a perfect Gaussian) [14]. 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 this mode in second harmonic lasing. It should be emphasized that no steering of the cavity mirrors or misalignment of the electron beam was used to produce this performance; it is the preferred mode of second harmonic lasing.

IV. Summary.—We have performed a study of laser gain where ironically, the "real world" effects of finite wiggler length and angles off-normal serve to increase performance over the ideal situation. 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 lead-thin 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 correlate with measurements of the derivative of the spontaneous spectrum, detuning lengths, and ratios from calculated spontaneous spectra.

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