Lasing in Forbidden Regions:

Second Harmonic FEL Oscillation

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Abstract

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. Although such lasing is ideally forbidden, since gain is zero on axis for a perfect electron beam in an infinite wiggler, the finite geometry allows sufficient gain in this situation 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 gain as calculated by different approaches.

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Introduction

We report the production, measurement, and initial characterization of a novel mode of operation using a high average power infrared free electron laser. In recent years, interest has developed in building fourth generation light sources (*1,2*) based on free-electron lasers (FEL) capable of producing x-rays needed to explore ultrafast phenomena such as atomic motion within a single atomic vibration – on the order of 100 fs. Such light sources could be used in many cross-disciplinary areas of research: material science (atomic motion/rearrangement during phase transitions), chemical reactions, and fast biological processes, to name a few. One method of getting shorter wavelengths from an 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(three times the fundamental frequency) (*3*), or even the fifth (five times) (*4*) 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(*5*). Even harmonic amplification has also been achieved in the microwave region in an over-moded waveguide utilizing a periodic position instability(*6*). 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 finite geometry terms which lead to off-axis gain. This is in agreement with predictions made over 16 years earlier(*7*).

The Infrared Free Electron Laser

Since this work is based on Jefferson Lab's high average power infrared free electron laser (IRFEL), a brief description is in order. The IRFEL 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 *(8)*. 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*(9)*, a full two orders of magnitude higher extracted power than other FELs.

The design of the machine is discussed in more detail elsewhere *(10)*, and the layout of the IRFEL is shown in Figure (1). The accelerator and laser parameters are summarized in Table 1. The accelerator produces a continuous train of ~1 ps-long bunches at a repetition rate of 18.7 to 75.5 MHz by accelerating them in high-performance srf cavities. The output beam energy can be up to ~48 MeV. The beam travels through the wiggler where the free-electron lasing action produces infrared light pulses of less than 1 ps amplified to saturation in oscillating between two mirrors forming an 8.0405-meter optical cavity. A small portion of the light is coupled out of both mirrors in the optical cavity. For this experiment total round trip optical cavity losses including such out-coupling were around 0.3%; 10% out-coupling is more typical.

Second harmonic Production - Concept

The basic physics of FEL lasing is well understood(*11,12*). 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). 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. The radiation then grows by $<n>^2$, where n is the number of bunched electrons, until non-linear processes take over and the system saturates. A Fourier analysis of the bunched electrons would reveal a spectrum rich in harmonics with a heightened spectral density at each of the harmonics of the fundamental (1, 2, 3, etc., times the initial frequency). Previous work has examined the spontaneous emission emitted at harmonics (termed "coherent spontaneous" radiation) when lasing in the fundamental(*13,14*). For even harmonics the emission on-axis is zero but emission off-axis can occur due to coupling to the electron beam's finite extent and betatron motion in the wiggler(*7*).

Gain exists at each of these harmonics and if it is sufficient to overcome system losses *and lasing at the higher-gain fundamental frequency can be suppressed,* then lasing at these harmonics can occur. This latter condition is not trivial to achieve. Bunching and gain at the fundamental is significantly larger than at higher harmonic frequencies so the FEL will tend to lase at the fundamental if it can. In previous work we achieved lasing at fifth harmonic by having the mirrors highly transmissive at the fundamental and third harmonic.

At the second harmonic where can the gain and coherence come from? There is zero gain of the beam on-axis for the even harmonics. This is most easily examined by looking at the relationship between the spontaneous emission and the gain. The spontaneous emission, that is the radiation that is emitted by a beam in traversing a wiggler before any subsequent amplification, is given by (*15*)

$$\frac{dI(\omega)}{d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left\| \int_{-\infty}^{\infty} dt \ \mathbf{n}\times(\mathbf{n}\times\boldsymbol{\beta}(t))\exp\left[i\omega(t-\frac{\mathbf{n}\cdot\mathbf{r}(t)}{c})\right]\right\|^2 \qquad (1)$$

in Gaussian units where $\frac{dI(\omega)}{d\Omega}$ is the power per electron per unit frequency interval per unit solid angle, e is the electron charge, c is the speed of light, t is time, **n** is the unit vector of the radiation with respect to the wiggler axis, **r**(t) is the electron trajectory and $\boldsymbol{\beta}(t) = \dot{\mathbf{r}}(t)/c$.

For a wiggler of N periods and harmonic K this can be shown to be

$$\frac{dI(\omega)}{d\Omega}\Big|_{\theta=0,\omega=k\omega_1} = \frac{N^2 e^2\gamma^2}{c}F_k(K)$$

with (2)

$$F_k(K) \equiv \frac{K^2k^2}{(1+K^2/2)}\left[J_{(k+1)/2}(\frac{K^2k^2}{(4+2K^2)}) - J_{(k+1)/2}(\frac{K^2k^2}{(4+2K^2)})\right]^2$$

for k odd

and $F_k(K) \equiv 0,$ for k even.

J refers to Bessel functions of fractional order.

In this, K is the wiggler strength parameter, $K = \frac{e}{\gamma mc^2\beta}\frac{\lambda_0 B_0}{2\pi}$

with B_0, λ_0 as the magnetic field strength and wavelength. In the forward direction the frequency spectrum contains all the odd harmonics of the fundamental lasing wavelength

$$\lambda_k = \frac{\lambda_0}{2k\gamma^2}(1 + K^2/2) \qquad k = 1,3,5,... \qquad (3)$$

As shown by Madey (*16*) and later experimentally confirmed by Elias (*17*) gain of the FEL is proportional to the derivative of the spontaneous field with respect to frequency.[2] Figure 2a shows the calculated spontaneous spectrum of the JLab FEL on-axis. Only a small amount of second harmonic light is predicted; this due to the finite length of the wiggler. When observing off-axis the situation changes somewhat. Since the electron motion is no longer exactly periodic there are even harmonic components to the spectrum which are enhanced. At some angles the gain at the second harmonic can even be higher than the fundamental. Figure 2b shows the calculated spontaneous spectrum 1.25 mrad off axis. Second harmonic intensity is enhanced by a factor of almost 20 while the fundamental has dropped only 20%. Previous, more accurate calculations(*19*) 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 we can estimate the relative gain of the fundamental and second harmonic as a function of angle; these are shown in Figure 3. 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

[2] See (*7*) for comments about the validity of the Madey theorem off-axis.

$\cosh(2\pi x/\lambda_0)$ leading to dilution of the resonant condition. This suggests a cavity mode that is small on center and maxima off-axis may preferentially occur. This was previously suggested for even harmonics lasing (6) and of what is termed "coherent spontaneous" emission, i.e. emission at higher harmonics during lasing on the fundamental (*13,14*). We see below that this is, in fact, what happens.

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 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 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 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. Under these conditions the mirrors are not highly reflective at the new fundamental wavelength of 6 microns but are highly reflective in the 3 micron region where the second harmonic is located. We scanned the cavity length and lasing commenced at the second harmonic. The lasing would only occur over a range of 0.6 microns. Figure 4 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 total optical cavity ringdown to be 162 +/- 10% passes for one e-folding. This corresponds to cavity losses of 0.62 % per pass. We also measured the rise time of the laser to be 16 microseconds from the 10% to the 90% point. Using the aforementioned loss this yields a maximum small signal gain of 1.35%. These values are consistent with the ratio of fundamental gain detuning width to second harmonic of roughly 40:1. It 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. 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 measured width of the spontaneous spectra was 40 nm or 1.37% compared to a 1/2N value of 1.24%. The calculated width of the second harmonic spectrum depends on the angles included but ranges from 0.9% on-axis to 2% at 1.25 mrad vertical offset.

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) unless the mirrors are operating at very high average powers(*20*). 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 lobes and a null in the center. Figure 5 illustrates this mode in second harmonic lasing. It should be emphasized that no steering of the cavity mirrors or mis-alignment of the electron beam was used to produce this performance; it is the preferred mode of operation in second harmonic lasing. By manipulating the mirror alignment by 5 μrad or less we could obtain lasing alternately in a higher order mode with a null on axis or in a TEM_{01}* "donut" mode with a hole in the center (Figure 6). 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.

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 one can achieve performance that matches projections. It is interesting that 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-thin beam of very small transverse dimensions ($\sigma\sim$ 560 μm 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.

Acknowledgement

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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. The specific parameters for the x-ray experiments are shown in the third column.

Electron accelerator		
Parameter	**Established capability**	**Second harmonic settings**
Kinetic Energy (MeV) tuneable	28.0 – 48.0	35
Average current (mA) tuneable	4.8	2.25
Bunch charge (pC) Tuneable	Up to 110	14 to 74 pC
Bunch length (rms) (femtoseconds)	300 - 500	~500
Peak current	Up to 60 A	Up to 60 A
Transverse Emittance (rms) (mm-mr)	7.5±1.5	7.5
Longitudinal Emittance (rms) KeV-deg	26±7	26
Pulse repetition frequency (PRF) selectable settings (MHz)	18.7, x0.25, x0.5, x2, and x4	18.7, 74.85 MHz

Free Electron Laser		
Parameter	**Established capability**	**Second harmonic settings**
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
Rayleigh range (cm)	40 +/- 2	40 +/- 2
Mirror radii (cm)	2.54	2.54
Mirror tilt tolerance (μrad)	~5	~2
Output Wavelength (μm)	1, 2.9-3.4, 4.8-5.3, 5.8-6.2	2.94
Mirror reflectivity (both) (%)	99.85	99.85

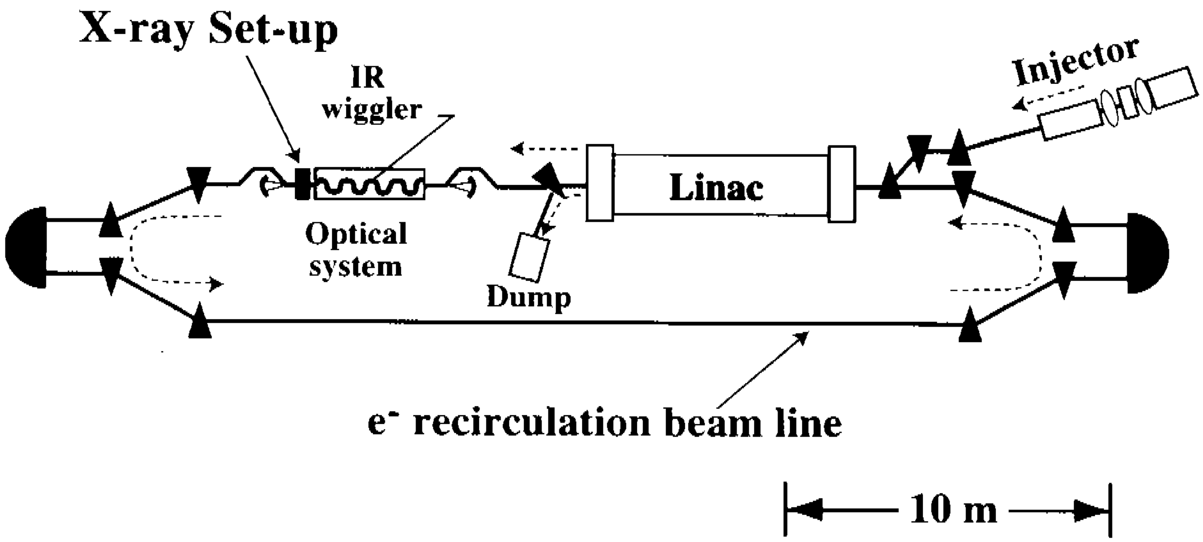


Figure 1: Layout of the Jefferson Lab Infrared Free Electron Laser (IRFEL). A photocathode-based injector generates sub-picosecond duration, 10 MeV energy, electron bunches for the superconducting rf (srf) linac that increases electron energies up to final energy tunable between 25 MeV and 48 MeV. Passing through the optical (cavity) system, the electrons produce IR radiation as they undulate in the wiggler region's alternating magnetic fields. The IR is captured and stored between high reflectivity mirrors of the optical (cavity) system, while the electrons are transported back around to the linac, re-inserted into the accelerator at 180-degrees out of phase with the accelerating rf, de-accelerated back to 10 MeV, and finally, deflected into a beam dump. This efficient design recovers rf energy and the residual radiation produced in the dump is minimized.

Figure 2: a) Calculated spontaneous spectrum of the electron beam passing though a wiggler at zero angle. Note the small level of second harmonic predicted. The production of second harmonic light is due to the finite length of the wiggler; in an infinite system the level would be zero. Calculations performed with SRW(*18*).

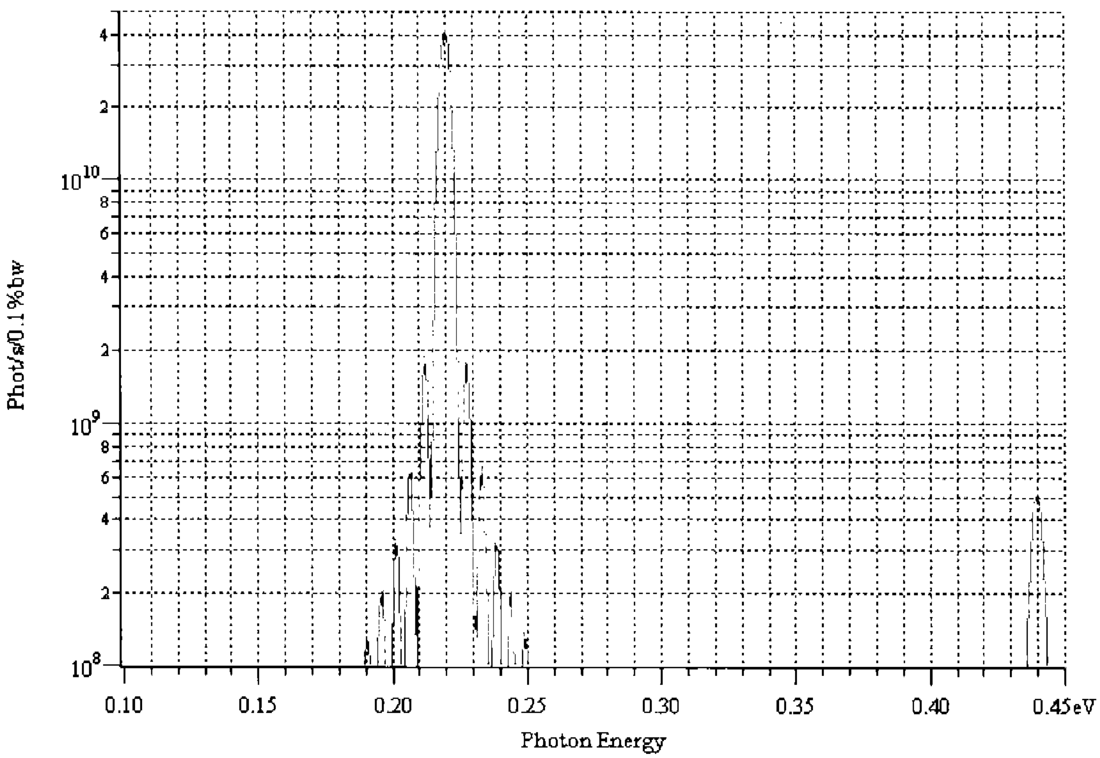


Figure 2: b) Calculated spontaneous spectrum of electron beam passing though the JLab wiggler observed 1 cm off axis vertically 8 m away (+1.25 mrad). (The wiggle direction of the electrons in this planar wiggler is the vertical direction.in this setup) Note the large increase in second harmonic predicted. . Calculations performed with SRW(*18*).

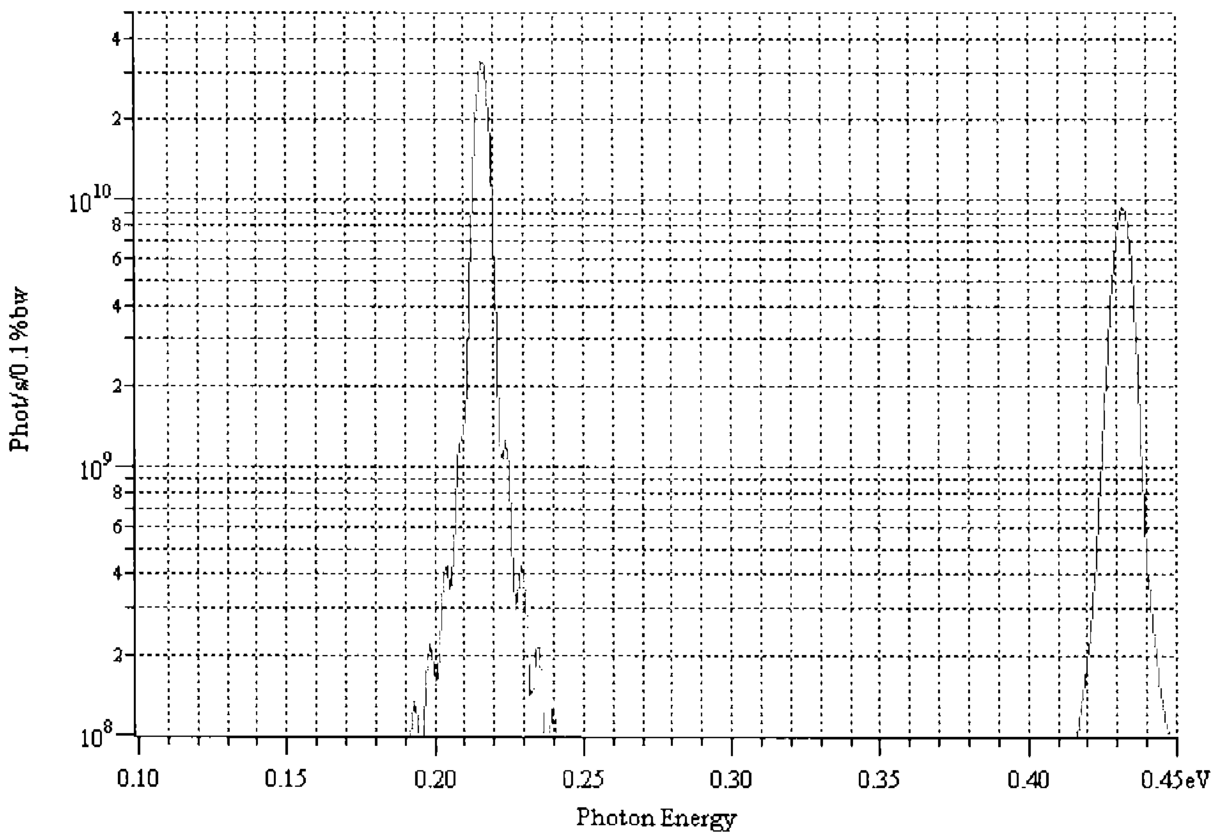


Figure 3: Relative peak gain estimated from the calculated spontaneous spectrum at the fundamental and second harmonic as a function of observer's angle off-axis in the horizontal and vertical planes.

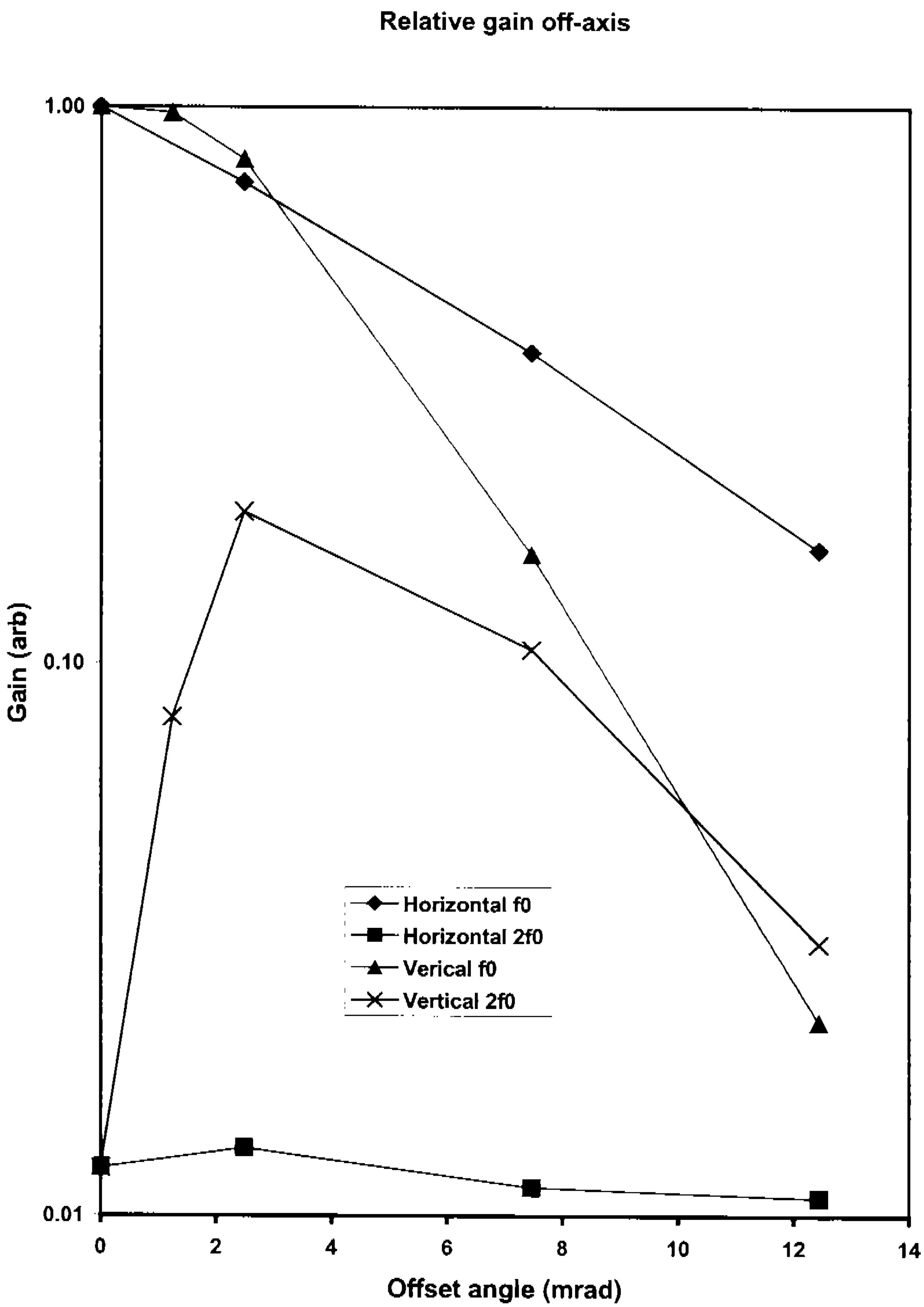


Figure 4: Second harmonic lasing spectrum displayed with the spontaneous spectrum under the same conditions. The vertical scales are arbitrary. No attempt was made to determine relative powers. The maximum average power during lasing was 3 watts. The predicted spontaneous power is on the order of nanowatts. Note that lasing occurs on the long wavelength (low energy) side of the spontaneous peak as expected.

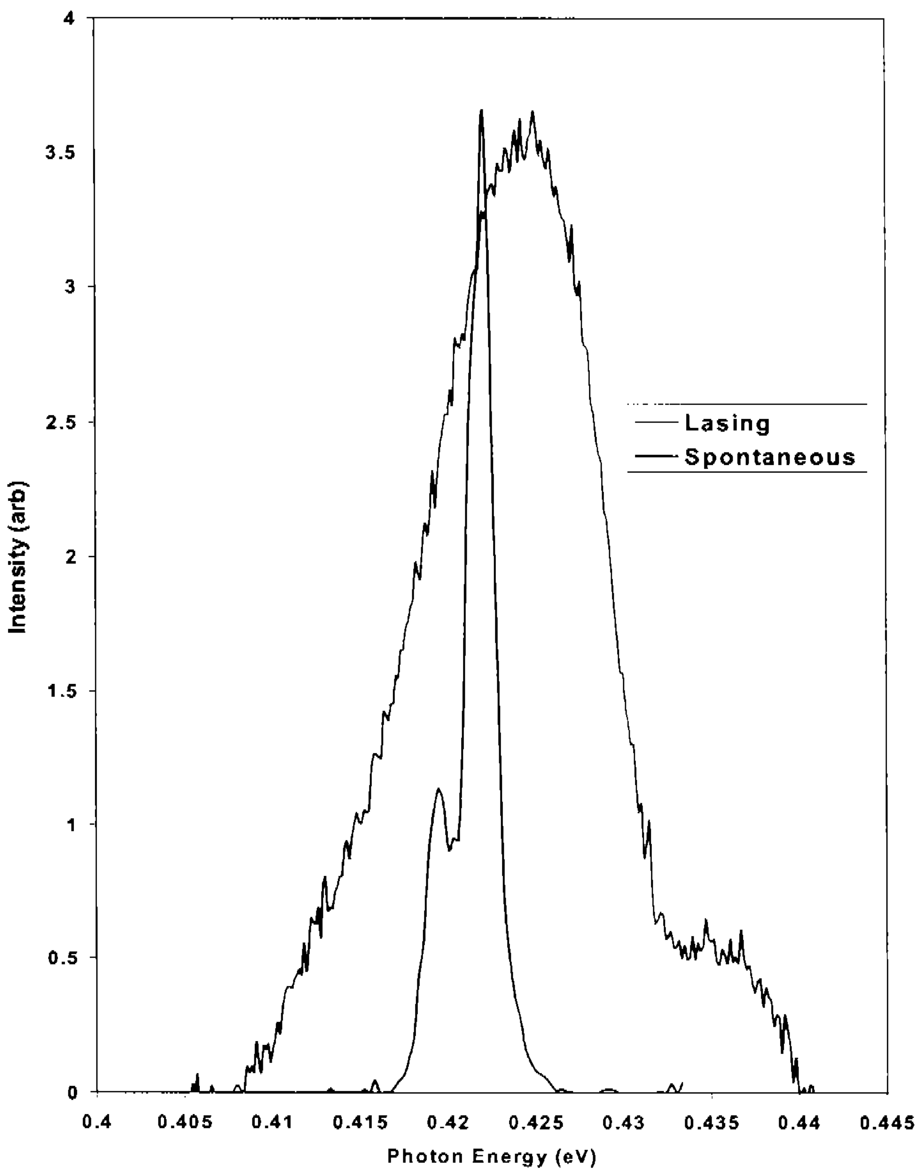
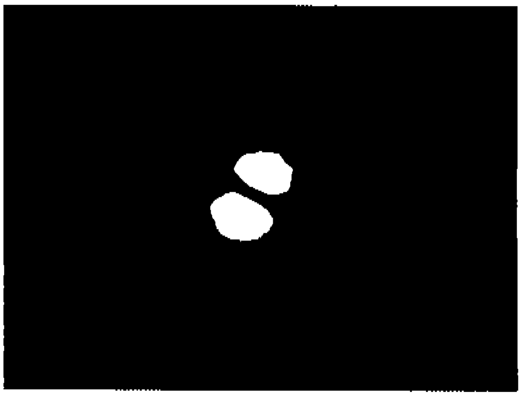


Figure 5: a) Infrared impinging on the optical beam dump power meter and b) false color image of the second harmonic optical mode in the TEM_{01} mode illustrating off-axis amplification. The relative azimuthal rotation has been altered for visual clarity.



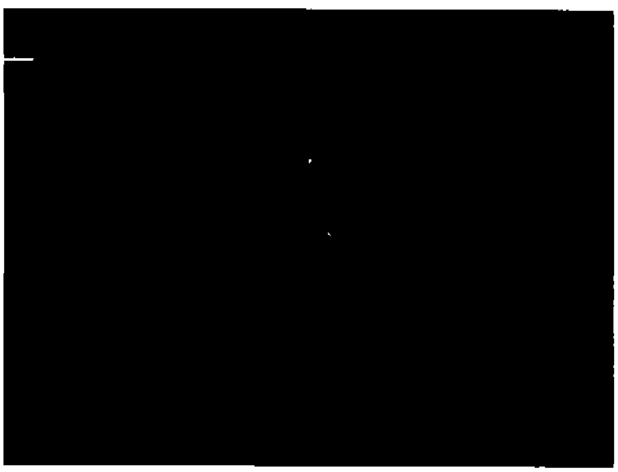


Figure 5: a) Infrared image of the second harmonic optical mode in the TEM_{01}* "donut" mode at highest gains