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TITLE: # LASING ON THE THIRD HARMONIC

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LASING ON THE THIRD HARMONIC*

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Abstract

The Los Alamos Free-Electron Laser has recently lased near 4 μm on the third harmonic of the fundamental frequency of about 12 μm. By a choice of intercavity apertures and cavity length, lasing can be forced to occur on both frequencies simultaneously or on either one alone.

1. Introduction

Lasing on harmonics of the fundamental frequency of a free-electron laser (FEL) is possible because of various anharmonic interactions taking place in the wiggler. Most important of these interactions is phase modulation of the fundamental radiation by a longitudinal oscillation of the electrons' positions [1] at twice the fundamental frequency. This phase modulation, in combination with the fundamental motion, generates all of the harmonics. It is possible to lase on any of them if conditions are right. The "right" conditions are adequate gain at the harmonic and the lack of interference from stronger lasing on the fundamental or other harmonics. The gain of a harmonic may be as large or larger than the gain of the fundamental. The important parameters are wiggler field strength, electron beam quality, and mirror reflectivity.

Lasing on the third harmonic has been attempted by two groups at Stanford University. The first group at Stanford [2], using the superconducting accelerator, produced lasing on the fundamental along with third harmonic generation that was weaker than predicted

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by theory if it represented lasing, but much stronger than theory if it was spontaneous emission. Other features of the emission puzzled the experimenters*: for example, its exaggerated sensitivity to various experimental parameters and the complex modal pattern of its shape. The second group [3] used the Mark III accelerator, a wiggler with a large gain, metallic mirrors, and an electron beam good enough to lase with almost equal strength on the first and third harmonic. Competition between these harmonics was avoided by inserting a dispersive dielectric slab into the optical beam so as to increase the optical path between mirrors by an amount that was different for the third harmonic and the fundamental. This strategem shifted the detuning curves so that the first and third harmonic lased independently at entirely different cavity lengths.

The interest in FELs at Los Alamos has centered on high optical power. We optimize power on the fundamental by pushing to high electron currents and accepting a degradation in the electron beam's energy spread and emittance that makes it poorly suited for lasing on any harmonic. To lase on a harmonic, therefore, it was necessary to increase the gain of the harmonic and to devise an especially effective method to eliminate interference from lasing on the fundamental. In this paper we will describe the equipment modifications made to accomplish these goals, describe the lasing results that were obtained, and we will analyse and discuss these results.

2. Equipment modifications

The FEL and accelerator were operated in the normal manner [4] except for the changes to be discussed. Fig. 1 shows a closeup photograph of the uniform period wiggler used. When this wiggler was built, provisions were made to change the field by altering the height of spacer blocks used to separate the top and bottom halves of the wiggler. We completely removed the blocks, thereby changing the wiggler gap from 8.8 to 5.8 mm, the peak field from 3.0 to 4.5 kG, and the peak K value from 0.8 to 1.1. Calculations

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* John Edighoffer, private communication.

made of the gain on the different harmonics with the new K value and normal values of beam current, emittance, and energy spread give 500% for the fundamental, 50% for the third harmonic, and very low values for the higher harmonics. Thus lasing probably could occur at both the fundamental and third harmonic wavelengths, but interference from the fundamental could be a serious problem.

We considered three techniques to discriminate against the fundamental: a dielectric slab, as Stanford had done; a special mirror with low reflectivity for the fundamental; and an aperture. We discarded the first two because of our uncertainty, based on hard experience [5], in the performance of dielectric materials in the intense beam of our laser. Instead, we chose to insert an aperture into the optical beam that would vignette and thus weaken the fundamental without seriously effecting the third harmonic. This discrimination was possible because of the expected difference in cross section of the two beams (a factor of 3). A series of calculations was performed to evaluate the discrimination of an aperture and to decide where it should be placed. The best placement was near the optical waists, and the discrimination that could be achieved was about a factor of 10, i e., marginally acceptable. Accordingly, a metal plate, shown in fig. 2, was inserted into the optical and electron paths just downstream of the wiggler. The plate contained a series of five holes of different sizes (0.45 to 0.25 cm diam, labeled #1 through #5). The plate was made thin (0.05 mm aluminum) to minimize scatter of electrons that unavoidably struck it. No problems caused by scatter or overheating of the metal plate were noted.

Copper mirrors were used, , one of which contained a 0.7 mm diam hole at its center to outcouple a small fraction of the light. The measuring apparatus included helium cooled mercury-doped germanium power meters and a grating spectrometer. The response of the measuring apparatus to the fundamental and third harmonic power levels inside the optical cavity was almost exactly the same. The grating spectrometer was blazed for the fundamental in the first order. This design automatically causes the third harmonic to be detected with high efficiency in the third order, and if the frequency of the third harmonic is exactly three times the frequency of the fundamental, their images will be superimposed at the output of the spectrometer. We can discriminate between light of different harmonics by inserting an optical filter into the beam. If both the fundamental and harmonic are produced in a micropulse of the same length, the transform-limited image of the third harmonic will be three times narrower than that of the fundamentals. If the fundamental and harmonic are both modified by a sideband of a fixed frequency, the third harmonic image will show a sideband separated by one third the spacing shown for the fundamental. One can see that the grating offers the opportunity to perform very precise measurements on important properties of both harmonics.

3. Results

Lasing was achieved on both the fundamental and third harmonic with no aperture and with apertures #1 through 4. No lasing at all occurred with the smallest aperture, #5. Thus, the original goal of supressing fundamental lasing with the aperture was not attained. Measurements were made of the decay rate (ringdown) of the fundamental and harmonic at the end of a macropulse. The experimental and calculated rates can be compared in table 1. Strong disagreement would indicate that a significant distortion of the optical modes existed, caused by the apertures or, perhaps, by refractive effects in the wiggler, but the agreement was good.

Detuning curves were made for both first and third harmonics by measuring their out coupled powers as a function of cavity length. We show typical measurements made with no aperture (fig. 3a), with aperture #1 (fig. 3b), and with aperture #3 (fig. 3c) and make the following observations:

1. The detuning curve for the fundamental has a "normal" width ($\sim$ 100 μm), but the width of the third harmonic is much narrower ($\sim$10 μm).
2. As we insert successively smaller apertures, the two detuning curves shift apart from strong overlap to complete separation.

3. The detuning curve for the fundamental is the only curve that shifts significantly, moving to shorter cavity lengths.
4. The efficiency of lasing on the fundamental is about 1%; on the third harmonic, efficiency of lasing is about 0.3%.
5. When no aperture is used, lasing on the fundamental is strong. The harmonic can be started or stopped by slight changes in alignment of the optical or electron beam. The best alignment for the fundamental appears to supress lasing on the harmonic.
6. When no aperture is used, lasing can occur simultaneously at both frequencies for the same value of cavity length.

One might expect a strong coupling to exist during simultaneous lasing so that the two frequencies (and phases) lock together. We looked for this coherence by examining the spectra. Unfortunately, the fundamental spectrum was broad whenever the harmonic was also present, being dominated by strong synchrotron sidebands. The third harmonic also appeared to be dominated by sidebands. The data are not definitive but fit a simple model in which the main line of the harmonic has a frequency exactly three times that of the fundamental and both lines are modulated by a synchrotron oscillation of the same frequency.

4. Discussion of results

A feature of this work is the separation of the harmonic and fundamental lasing achieved by the aperture. We need to know how this comes about. Calculations have been made of the consequences of the aperture's vignetting. The most obvious consequence is attenuation of the beam, but of equal importance is distortion of the shape that mixes in higher order transverse modes. We believe that the mixing of higher modes causes the shift of the fundamental's detuning curve. The reasoning is as follows: The cavity modes are characterized by a phase shift that occurs near the mode's waist in excess of the normal phase shift that occurs for a plane wave [6]. For one round trip in the cavity, this extra phase shift amounts to about 2π for the lowest (even) Gaussian mode, 4π for the next (odd) mode, 6π for the next (even) mode, and an additional 2π for each higher mode. The exact value of the phase shifts differs slightly from these values and depends upon the cavity's Rayleigh range. Because of these extra phase shifts, the group velocity of the optical micropulse is reduced so that the distance between the mirrors must be shortened. Our estimates show that, because of this effect, fundamental light generated in the lowest Gaussian mode needs a cavity about 5 μm shorter than otherwise expected; light generated in the second lowest mode, 10 μm shorter; etc. If some combination of modes is present, an average adjustment of cavity length would have to be made. Calculations we have made show that aperture #3 mixes in roughly equal amounts of the four lowest even modes at the fundamental frequency but causes little mixing of the third harmonic modes. One would, thus, expect the synchronous cavity length for the fundamental to shift to a shorter length by an amount around 20 μm, while the third harmonic would hardly shift at all. The two detuning curves would, therefore, separate from each other by about 20 μm, in agreement with the observations. Mixing in higher transverse modes also stretches the micropulse by about four cycles, but because its length is 300 cycles (10 ps long), the stretch is negligible. Larger apertures should produce less shift of the detuning curve; smaller apertures should produce more, all in good agreement with the observations. Several other studies have emphasized the importance of the relative phase shifts of the higher order modes—among them, studies of the walking and breathing modes [7] and of supression of mode distortions by a careful choice of Rayleigh range [8].

A thorough treatment of mode distortions and group velocities requires a detailed understanding of cavity modes and the effects of the electron beam on these modes. The discussion we have presented is meant as only an introduction to the topic.

5. Conclusions

An aperture is a rugged flexible device that can be inserted into any FEL and provides a significant (about 10 times) discrimination against fundamental lasing. Its use allows one the freedom to choose either separate lasing on the fundamental or on the harmonic or simultaneous lasing on both. Simultaneous lasing provides the opportunity to investigate novel phenomena such as coupling between the two frequencies.

Acknowledgments

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Figure Captions

Fig. 1. Uniform wiggler used in experiment.

Fig. 2. Aperture plate on actuator.

Fig. 3a. Detuning curves with no aperture.

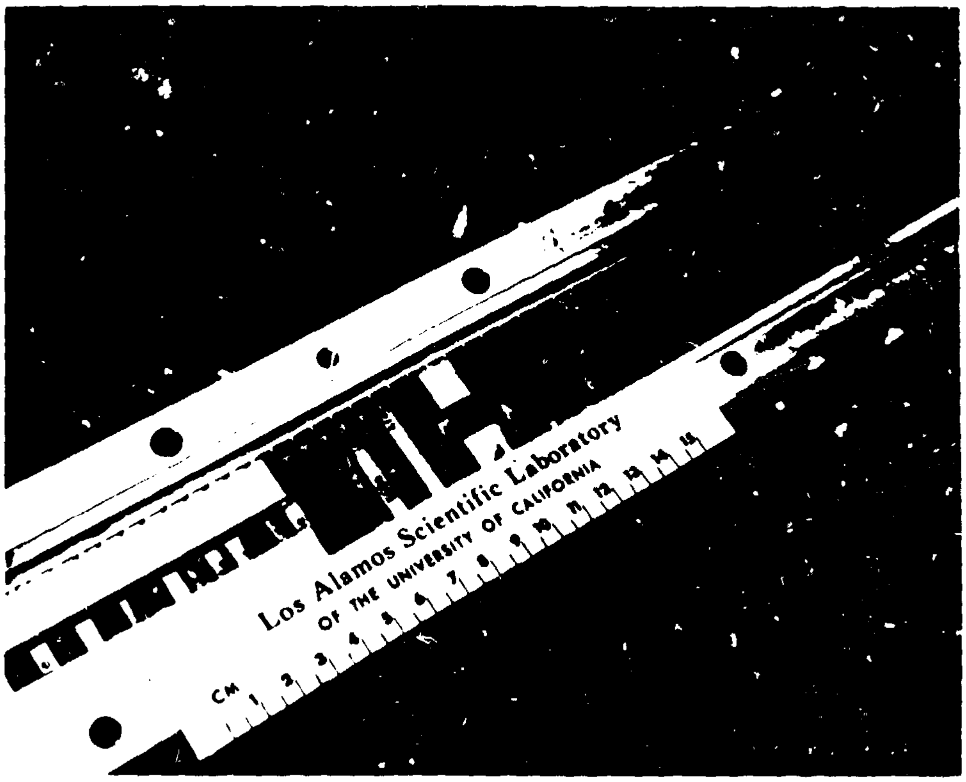
Fig. 3b. Detuning curves with largest aperture, #1.

Fig. 3c. Detuning curves with small aperture, #3.

Table 1

Sizes of different apertures as well as their calculated and measured losses at 10 and 3 μm.

Aperture	Dia. (mm)	Calculated loss/pass		Measured loss/pass	
		10.8 μm	3.6 μm	10 μm	3 μm
none		25%	3.9%	15%	6%
#1	4.5	36%	4.0%	29%	4%
2	4.0	50%	5.0%	35%	5%
3	3.5	64%	7.0%	50%	7%
4	2.9	75%	13.0%	75%	NM
5	2.5	86%	23.0%	—	—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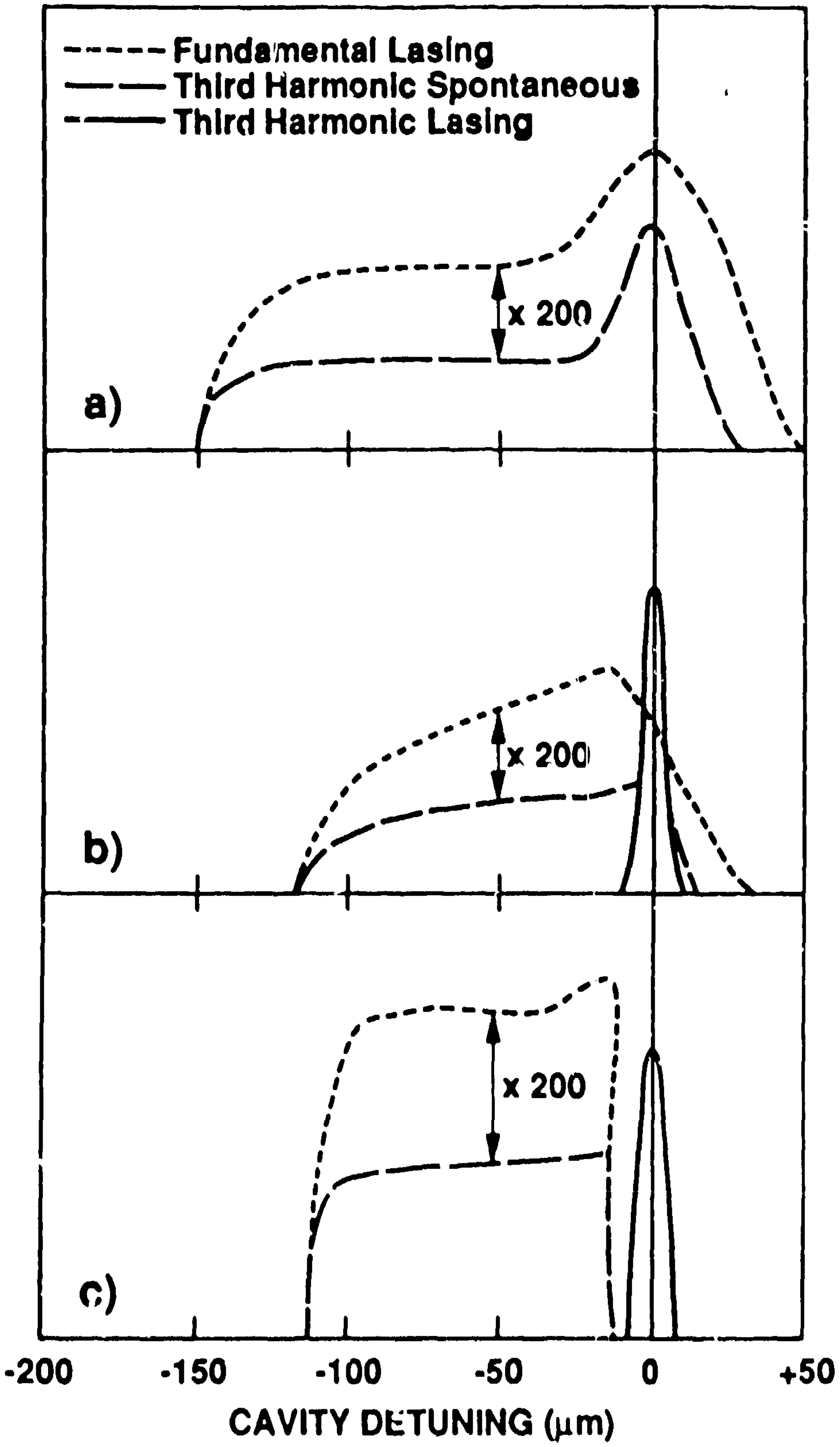
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Fig 2



Fundamental Lasing
Third Harmonic Spontaneous
Third Harmonic Lasing
x 200
a)
x 200
b)
x 200
c)
-200
-150
-100
-50
0
+50
CAVITY DETUNING (μm)