HARMONIC LASING CHARACTERIZATION AT JEFFERSON LAB

S. V. Benson and M. D. Shinn, Jefferson Lab, Newport News VA 23606.

Abstract

Harmonic lasing is normally suppressed because of lasing at the fundamental wavelength. It can, however, be achieved using any of several methods that suppress fundamental lasing. In this paper we discuss two methods used at Jefferson Lab. The first is to use the characteristics of dielectric coatings to allow harmonic lasing at cavity lengths longer than the synchronous length for the fundamental. The second is to use a dielectric coating that has little reflectivity at the fundamental. This allows us to directly compare fundamental and harmonic lasing with the same optical resonator and electron beam. We present measurement carried out at Jefferson Lab using the IR Upgrade FEL operating at 0.53, 0.94, 1.04, 1.6, and 2.8 microns in which both schemes are used to produce lasing at both the 3rd and 5th harmonic of the fundamental.

INTRODUCTION

Harmonic lasing was predicted in 1980[1][2] and third harmonic lasing was demonstrated at Stanford and Los Alamos [3][4] in 1988. Since then many groups have demonstrated 3rd harmonic lasing and Jefferson Lab has demonstrated 2nd and 5th harmonic lasing as well [5][6]. In all cases the challenge has been two-fold: produce a sufficiently bright electron beam with high gain at harmonic wavelengths, and somehow suppress fundamental lasing. Photocathode injectors now routinely produce electron beams bright enough to lase well at harmonics. There are also several techniques that are available to suppress the fundamental. The first harmonic lasing demonstrations used a dispersive element to force the harmonic lasing to a longer cavity length or an aperture to preferentially diffract away the fundamental. Another way, more appropriate for a high power system, is to use dielectric mirrors to provide a high resonator Q at the harmonic and little or no Q at the fundamental. This is how lasing at the second and fifth harmonic were achieved at Jefferson Lab. In either case the gain was quite low so two high reflectors were used to produce lasing.

In this paper dielectric mirrors were used to produce harmonic lasing with relatively high gain at the third and fifth harmonic and a new mechanism was discovered that produces harmonic lasing using a resonator with high Q at the fundamental.

FEATURES OF DIELECTRIC MIRRORS RELATED TO HARMONIC LASING

Most high power resonator mirrors consist of a stack of layer pairs. The layers alternate between high and low refractive index materials, for example silicon dioxide/hafnium dioxide or thorium fluoride/zinc selenide. The thickness of each layer is one quarter of the center wavelength, or $\lambda/4n$ where n is the refractive index of the coating. The peak reflectivity is a function of the ratio of the refractive indices and the number of layer pairs. The spectral width of the reflectivity band is proportional to the square root of the ratio of the refractive indices. Note that the third harmonic center wavelength is not exactly one third of the fundamental wavelength because the refractive indices vary with wavelength, however in practice, if a quarter wave stack has good reflectivity for one wavelength, it will have similar reflectivity at the third harmonic of that wavelength.

As for the laser cavity, if a resonator has a high resonator Q at the fundamental wavelength, then it usually has high resonator Q for the third harmonic and possibly the fifth harmonic if the fundamental is a long wavelength. In our case the resonator Q is actually slightly higher for the third harmonic than for the fundamental. Since the gain at the fundamental wavelength is typically much higher than the third and fifth harmonic gain, the laser will almost always lase at the fundamental with a quarter wave stack. If the wiggler is set to a wavelength 5/3 as long as the center wavelength of the quarter wave stack coating, the third harmonic of the coating will be coincident with the fifth harmonic of the FEL. There is very little resonator Q at 5/3 of the center wavelength or at 5/9 of the resonator wavelength where the third harmonic is resonant. The laser then lases at the fifth harmonic of the FEL and the third harmonic of the coating. Note that it is also possible to lase at the fundamental of the FEL with the third harmonic of the coating.

CASE 1. LASING AT HARMONICS AT A FIXED WAVELENGTH

The first measurements were performed with the same resonator and center wavelength, while varying the wiggler strength. The resonant wavelength of the wiggler was set to 1.02 microns, 3.06 microns, and 5.1 microns. All three settings produced strong lasing. The detuning curves for the three settings are show in figure 1. It is very interesting to note that the fundamental, which has the highest gain of the three, has the shortest detuning curve. According to G. Dattoli's formulas [7], the detuning curve length should be proportional to $GhN_W\lambda$. where G is the small signal gain, h is the harmonic number, N_W is the number of wiggler periods and λ is the laser wavelength. The ratio of the detuning curve lengths using the measured gain should be 3.5:6.0:5.7 according to the formula. The third and fifth are a bit shorter than this would indicate but they are also closer to threshold, which shortens the detuning curve.

Table 1 shows a comparison of measured and predicted gain and power, where predicted values were obtained using Dattoli's formulas. The measured gain was inferred from the minimum turn-on time in the detuning curve. Simulations indicate that the turn-on time to half power is 22.5 e-foldings and direct measurements of the gain support this observation. The power was measured using a high power laser power meter accurate to 5%. The gain and power are in good agreement for the fundamental and fifth harmonic but the experimental gain is lower and power is much larger than predicted for the third harmonic. This may have been due to differences in accelerator setup though no single accelerator parameter can explain the discrepancy.

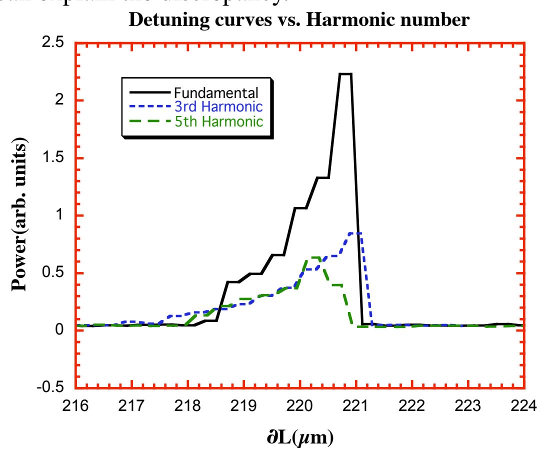


Figure 1. Power vs. cavity length for lasing at the fundamental, third, and fifth harmonic, with fundamental wavelength ~1.04 μm.

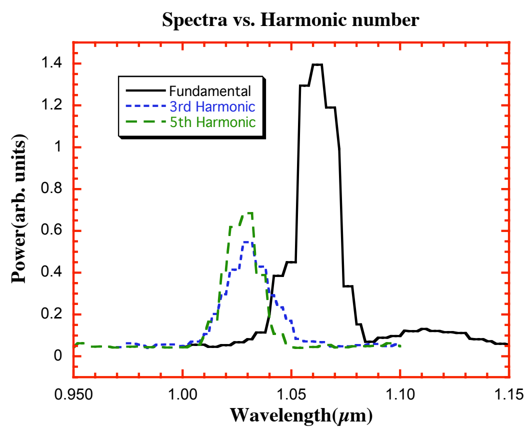


Figure 2. Spectra while lasing with 1.06 micron mirrors with the resonant wavelength equal to 1.02, 3.06, and 5.1 microns. The resonator losses were 3.5%/pass. Note the movement towards 1.02 microns as the harmonic number is increased.

Table 1. Measured and predicted gain and power when lasing at harmonics at ~1.04 microns.

h	Meas. Gain	Calc. Gain	Meas. Power(W)	Calc. Power (W)
1	48%	48%	700	885
3	20.4%	24%	275	180
5	11.6%	11%	63	65

Spectra for these three cases are shown in Figure 2. Note that the wavelengths are not the same. Simulations indicate that the lasing wavelength is typically a fraction $1/hN_W$ longer than the resonant wavelength. Since h is changing but the resonant wavelength is not, one expects the laser wavelength to get closer to the resonant wavelength. The fundamental is shifted further from the resonant wavelength because it is lasing harder than the harmonics, as is evident from the weak sideband at 1.11 μm.

CASE 2: LASING ON THE FIFTH HARMONIC OF THE LASER AND THE THIRD HARMONIC OF THE COATING

For both the 2.8 and 1.6 micron mirrors, it was possible to lase at the third harmonic of the laser coating and the fifth harmonic of the laser. For the 2.8 micron mirrors the wiggler was set to 4.65 microns and lased at 0.935 microns. For the 1.6 micron mirrors the wiggler was set to 2.74 microns and lased at 0.53 microns. In both cases the lasing was quite robust. Note that both mirror sets have higher reflectivity at the third harmonic than at the fundamental. The detuning curve at 0.53 μm was as long as 5 microns, which is comparable to the fundamental lasing curve. Dattoli's formula noted above, implies that the 5th harmonic gain is 3/5 of the fundamental gain. The gain inferred from the turn-on time and losses is about 1/3 the fundamental gain. Direct gain measurements will be necessary to resolve these discrepancies. The efficiency was not as good as the 1.06 micron lasing but we did obtain 35 W of CW light in the green.

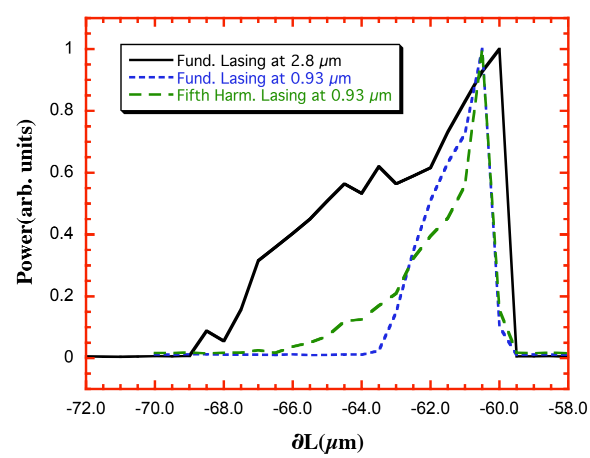
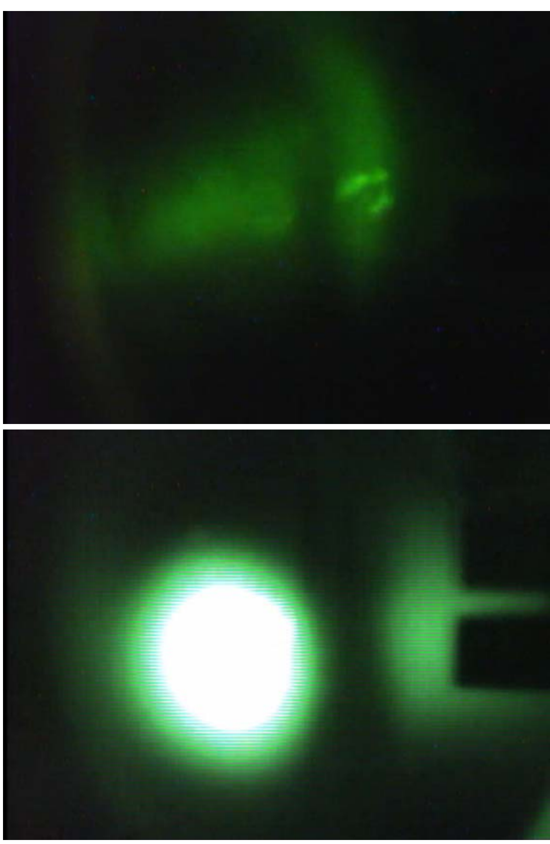


Figure 3. Detuning curves for three different configurations using the 2.8 micron mirrors.

In figure 3 we show the detuning curves while lasing at the fundamental using both the 2.8 μm and 0.935 μm reflectivity peaks. The detuning curves for the fundamental have a three to one ratio. Dattoli's formula then would indicate similar gain. In fact the gain at 2.8 microns is about 50% larger than at 0.935 microns. This apparent discrepancy has been seen before when varying the electron beam repetition rate [8]. Both curves have a convex shape (negative second derivative), which is common when the gain is well above threshold. The fifth harmonic curve at 0.935 μm should be five times as long as the fundamental if the gain is similar. In fact it is only twice as long indicating a gain 40% of the fundamental. It also has a concave shape, which is typical for lasing close to threshold. The ratio between the fifth harmonic gain and fundamental gain is extremely sensitive to the energy spread. The ratio is 0.4:1 for an energy spread of 0.3%. This is a typical value for our machine, though the spread was not measured the day of these measurements.

CASE 3: A NEW WAY TO LASE AT THE THIRD HARMONIC

When the laser is very well tuned and the wavelength is very close to or slightly longer than the center wavelength of the mirror coatings, we see a very interesting phenomenon. The laser starts to lase sporadically at the third harmonic when the cavity length is very close to the synchronous cavity length where the round trip time in the resonator matches the arrival time of the electron bunches. This occurs for both the 1.6 micron and 2.8 micron mirrors. We sometimes use this as a measure of how well the laser is optimized. If the laser optimization is poor, harmonic lasing will not occur.



a.

b.

Figure 4. (a) coherent harmonics emitted during fundamental lasing on the output coupler of the laser. (b) Harmonic lasing at 0.53 microns obtained by lengthening the optical cavity by a fraction of a micron.

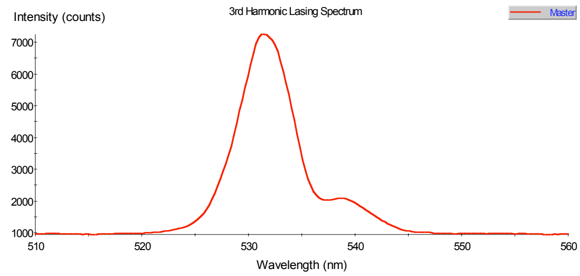


Figure 5. Lasing spectrum using an Ocean Optics visible spectrometer array. This is a single macropulse shot.

This behavior is shown in figure 4. In figure 4a we see the pattern of coherent spontaneous radiation that is always present when lasing at 1.6 microns. In figure 4b we have lengthened the optical cavity by a fraction of a micron and see very strong green emission with a TEM_{00} profile. The image here completely saturates the CCD camera. The spectrum of the third harmonic lasing is shown in Figure 5. This signal at 530 nm is not present when the cavity is tuned for strong fundamental lasing.

With the 2.8 μm mirrors the lasing can occur over a larger range of detuning and can be quite stable. In figure 6 we show a detuning curve obtained using a spectrometer at 0.935 microns. The detector did not show any signal when lasing at the fundamental but showed a strong signal when lasing at the 3[rd] harmonic.

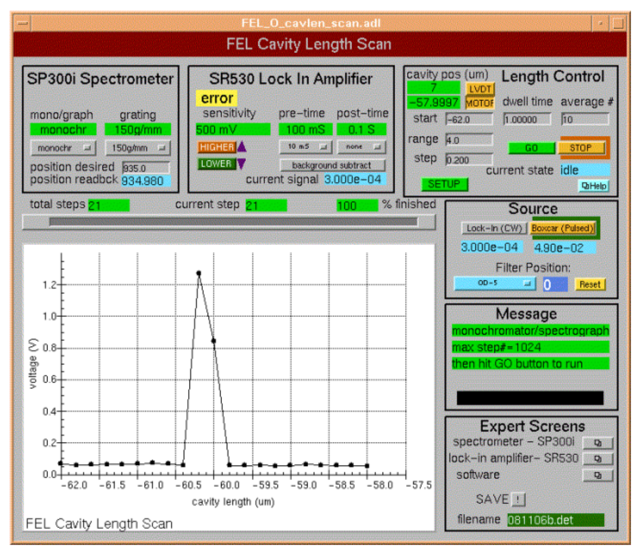


Figure 6. Detuning curve taken through a spectrometer set to 935 nm. The lasing occurs over about 0.5 microns in cavity length. The fundamental is not lasing over this range.

We do not understand exactly how this new lasing phenemonan works. It seems as though the round trip time in the resonator is less for the third harmonic than for the fundamental. This suggests that the fundamental light penetrates more deeply into the coating than the third harmonic light. The interference that produces the outgoing wave should be the same for the third harmonic as for the fundamental. The different penetration depth may be related to the higher reflectivity of the coating at the third harmonic. Future experiments will study the wavelength dependence of the harmonic lasing and compare with reflectivity models of the coating.

CONCLUSIONS

The availability of a high brightness electron beam and a wiggler with large tuning range has opened up an interesting diagnostic device for free-electron lasers. Since the harmonic lasing is far more sensitive to beam parameters than the fundamental it allows one to more carefully optimize the laser. The presence of lasing at harmonics greatly restricts the laser modeling since the model must fit both the fundamental and harmonic lasing with the same optical resonator and electron beam.

In the future we plan to try to lase with an electron beam with half the energy spread of the one now used. This reduces the fundamental gain but greatly increases the harmonic gain. We should have a situation where the harmonic gain actually exceeds the fundamental gain. This should also allow lasing at the seventh and possibly the ninth harmonic.

ACKNOWLEDGEMENTS

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