Direct Spectral Measurements of a Quasi-cw Free-Electron Laser Oscillator

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Mode competition in a far-infrared, free-electron laser operating in the quasi-cw regime has been investigated by means of direct spectral measurement with a heterodyne receiver system. About 30% of the spectra had a single longitudinal mode. The observed data compare reasonably well with theory. It is found that even in a regime of multimode operation the laser signals are only weakly modulated in time, as observed with a video detector. Such an observation is consistent with a phase locking of multiple modes, as predicted by theory.

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One of the most important issues of free-electron laser (FEL) physics is the complex nonlinear interaction between different resonator modes and the electron beam.[1-6] This can be thought of as a competition between modes for the beam's energy. It exists primarily between longitudinal modes, but may involve transverse modes as well, and can result in complex time-frequency behavior.[3] The choice of FEL operating parameters has profound influence on such behavior which in turn affects the ultimate success in achieving goals such as highly coherent, single-frequency operation or frequency tuning agility.

The issue of mode competition applies to a wide variety of free-electron generators of coherent radiation. In conventional gyrotrons, for example, competition between transverse modes of highly overmoded closed resonators is a primary concern in obtaining high efficiency operation.[7] In quasioptical gyrotrons, mode competition between axial modes is a significant problem.[8]

In this Letter, we present results of the first direct spectral measurement of the output radiation from the FEL oscillator at the University of California, Santa Barbara (UCSB). This FEL is unique in employing a recirculating-beam electrostatic accelerator operating in the microsecond pulse regime. The absence of a picosecond temporal microstructure, characteristic of most FELs, means that the usual Fourier-transform linewidth limitation of a few tenths of a percent does not apply. This opens the possibility of generating extremely coherent radiation for applications such as spectroscopy or isotope separation. Pertinent to the linewidth issue are the FEL's Fabry-Pérot-type resonator characteristics. For gain bandwidths greater than the free spectral range $\nu_{FSR}=c/2L$, linewidth is a function of the number of modes lasing. For gain bandwidths less than ν_{FSR}, only a single mode lases and an upper limit on the linewidth is determined by the Airy function response, $1/\{1+\mathcal{F}\sin^2\delta/2\}$, where $\delta=4\pi L_r/\lambda_u$ and $\mathcal{F}=4\sqrt{1-l}/(1-\sqrt{1-l})^2$, resulting in $\Delta\nu=c/\pi L_r\sqrt{\mathcal{F}}$. For the UCSB resonator of length $L_r=7.75$ m and loss $l\approx 10\%$, $\nu_{FSR}=19.3$ MHz, and the linewidth of a single longitudinal mode is $\Delta\nu=3.5\times10^5$ Hz or $\Delta\nu/\nu\simeq 2\times10^{-7}$. The actual single-mode linewidth may be even narrower since the lasing can be characterized as a stimulated-emission process with line narrowing proportional to intensity.[9]

The UCSB FEL operates in the far-infrared portion of the spectrum necessitating use of an overmoded waveguide as part of the resonator ($h_y/\lambda\approx 100$). Despite the large number of transverse modes available in such a guide, only a small number of frequencies[3]

$$\nu_{n,m}=\frac{c\epsilon_m}{\lambda_u}\frac{\beta_z}{1-\beta_z^2}\times\left\{1\pm\beta_z\left[1-(1-\beta_z^2)\left(\frac{n\lambda_u}{2b\beta_z\epsilon_m}\right)^2\right]^{1/2}\right\} \quad (1)$$

satisfy the FEL synchronism condition, where $\epsilon_m=1-(m+\frac{1}{2})/k_0z_r$, n and m are mode indices, b is the resonator height, λ_u is the undulator period, k_0 is the wave number, z_r is the Rayleigh length, and $\beta_z=v_z/c$ is the average axial electron velocity. Longitudinal modes, however, are more numerous, occurring at frequency intervals of 19.3 MHz. The FEL small-signal gain is of the form

$$G_{ss}\propto-\frac{d}{d\mu}\left(\frac{\sin^2(\mu/2)}{(\mu/2)^2}\right),\qquad \mu\simeq 2\pi N_u(1-\nu/\nu_0)\,, \quad (2)$$

where μ is the FEL resonance detuning parameter, ν_0 is the FEL resonance frequency, and N_u is the number of undulator periods. Since G_{ss} is positive for $0<\mu<2\pi$, there are approximately 500 longitudinal modes that can exhibit gain. In practice, only modes near the highest portion of the curve have sufficient gain to lase. It has been observed that the FEL start-up frequencies, at a given energy, fit a Gaussian curve with a fractional width of $\approx 0.05\%$ FWHM. This includes about 75 longitudinal modes.

The UCSB FEL exhibits the additional complicating characteristic of a continuous negative slewing of beam energy of ≈ 1 kV/μs caused by the discharge of its accelerator terminal voltage. As a result of this, rather than continuously shift between adjacent modes, the lasing establishes itself on one or more modes for $\approx 1-3$ μs and then, when the resonance condition has shifted so far that there is no longer gain to support lasing at those frequencies, jumps over about 100 modes to lase on a new frequency. For long pulses, the laser steps through a series of descending frequencies.[10]

Initial interpretation of the UCSB FEL data as indicating single-mode operation[3] was based on inference from time-domain measurements. One of the most striking features of the FEL's operation has been a radiation pulse whose amplitude is relatively free of modulation. This was thought to be consistent with lasing on a single mode with adjacent modes smaller than a few percent and with a very narrow linewidth whose coherence time was comparable to pulse length. Similar behavior was observed in a low-frequency FEL experiment at Hughes Research[11] where single-mode operation was more readily confirmed at microwave frequencies (30 GHz). In the case of the UCSB machine, it subsequently became apparent that the loss of phase information by the square-law detection processes might undermine the validity of that interpretation. In particular, the appearance of amplitude coherence in the time domain might be possible if more than one mode were lasing but with a specific phase relationship between modes.[5] Numerical simulations[4] suggest that this is possible with many modes simultaneously lasing.

The need for a direct frequency-domain spectral measurement at UCSB has long been recognized but conventional spectrum analyzers were inappropriate due to the microsecond time duration of lasing. The stochastic nature of the FEL start-up resulted in a pulse-to-pulse frequency fluctuation which precluded spectral measurement by sampling techniques.

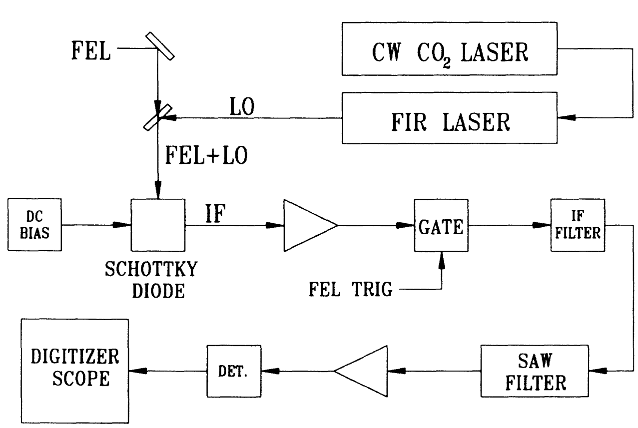

FIG. 1. Block diagram of the heterodyne receiver and SAW spectrometer system.

The spectrometer employed for these studies consisted of a heterodyne receiver and a surface-acoustic-wave (SAW) dispersive-delay-line filter developed at MIT. This system, shown in Fig. 1, permitted essentially instantaneous, direct single-pulse measurement of the spectrum. The heterodyne receiver consisted of a Schottky diode which mixed the radiation from the FEL with that from the local oscillator, a cw far-infrared methyl alcohol gas laser operated at 163 μm and pumped by the $10R38$ CO_2 line. The parameters of the FEL operation during this study are listed in Table I.

The FEL was tuned to yield an intermediate frequency (IF) ν_{IF} from the mixer at approximately 1 GHz. For fundamental mixing, the local oscillator frequency ν_{LO} and the FEL frequency ν_{FEL} are related to the IF frequency by $\nu_{FEL} = \nu_{LO} \pm \nu_{IF}$. The IF signal was amplified and gated to a pulse of width $\tau = 100$ ns by a fast *p-i-n* diode switch. The surface-acoustic-wave dispersive filter, with a center frequency $f_0 = 1$ GHz and a bandwidth $\Delta f = 400$ MHz, produced a frequency-dependent time delay of $\Delta t = 8.3\ \mu\text{s} - (0.02\ \mu\text{s/MHz})(f - f_0)$. The temporally dispersed output from the SAW filter represents the spectrum of the IF input signal provided the gated IF pulse width τ satisfies the inequality $\frac{3}{2}(T\Delta f)^{1/2} \approx T/\tau \leq \frac{1}{4}(T\Delta f)$, where T is the total SAW delay time. In this case, $\tau = 100$ ns, $T = 8$ μs, and $\Delta f = 400$ MHz, satisfying the above inequality. After amplification, the IF signal is detected by a fast diode and recorded by a 100 MHz/s digitizer. Corrections for the SAW device's frequency-dependent attenuation and the detector diode nonlinearity are applied during data analysis.

The resolution of the SAW spectrometer was approximately 8 MHz. Consequently, individual longitudinal modes were easily resolved but the actual linewidth could not be determined. The bandwidth of the SAW spectrometer was sufficient to observe as many as twenty modes on a single pulse. However, as mentioned previously, the stochastic nature of the FEL start-up and imperfect pulse-to-pulse beam energy regulation permitted lasing on any of about 75 modes described by a Gaussian

TABLE I. FEL parameters for spectral measurement.

FEL parameter	Value
Frequency, ν_s	1.83 THz
Beam energy, E	4.9 MeV
Beam current, I_b	2.4 A
Period, λ_u	3.6 cm
No. of periods, N_{per}	160
Undulator length, L_u	5.76 m
Resonator length, L_r	7.14 m
Pulse length, t_p	1–2 μs

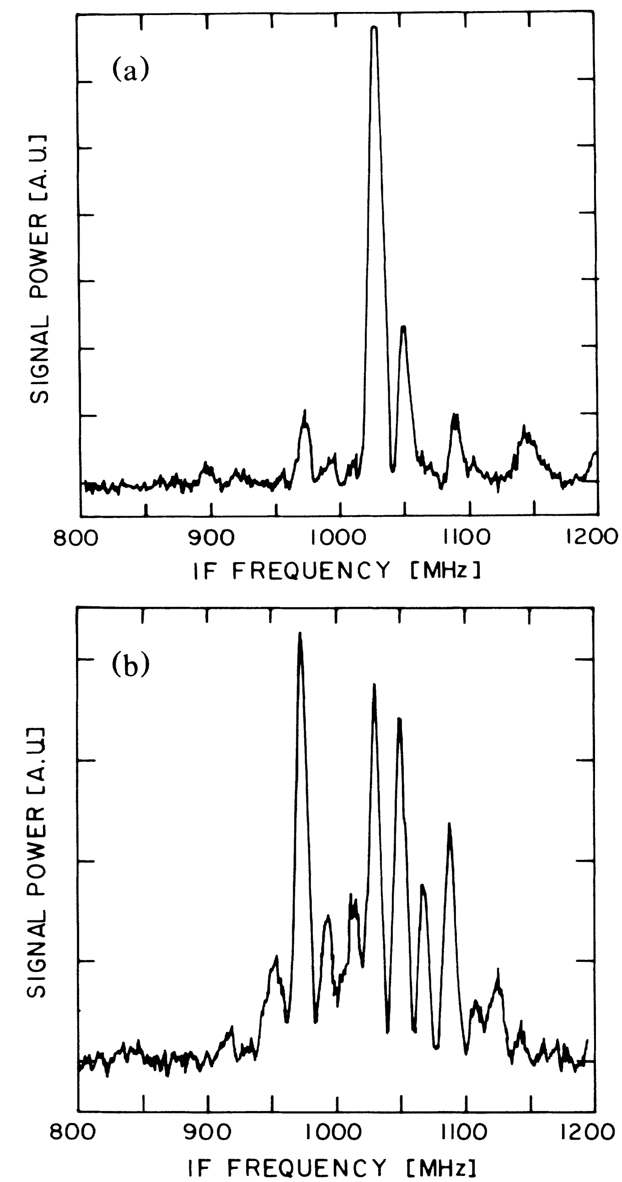

FIG. 2. Typical mode spectra showing (a) single-mode lasing and (b) multimode operation.

distribution of FWHM $\simeq 0.05\%$. Thus, the lasing frequency did not always fall within the spectrometer bandwidth.

Approximately ninety spectra were taken during this study. Two typical spectra are shown in Fig. 2. Spectra were acquired at times t during the FEL pulse, as shown in Fig. 3, corresponding to time of saturation and four earlier times with $\Delta t = t_{\text{sat}} - t = 0$, 320, 500, 700, and 1100 ns, where t_{sat} is the time of saturation of the optical pulse. The results of a statistical analysis of the spectra are shown in Fig. 4, a histogram of the number of spectra as a function of N for which there are N longitudinal modes excited with powers greater or equal to 50% of the power ($F=2$) of the largest mode. By this criterion, approximately 29% of the spectra showed single-mode lasing.

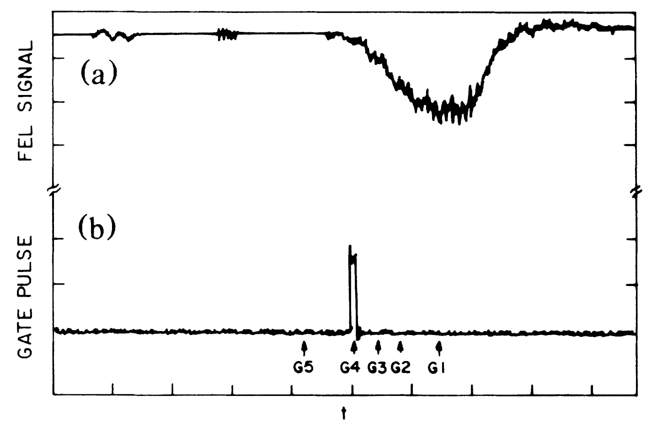

FIG. 3. (a) FEL radiation pulse and (b) SAW gate pulse, showing their relative timing.

In attempting to interpret these results, two essential features stand out. First, the presence of strong mode competition is confirmed. A continuum of excited modes is never seen. Second, the excitation of the modes is highly stochastic. Every FEL pulse produced a dramatically different mode distribution. No clear patterns were discernible.

With respect to mode competition, a third-order perturbation expansion of the FEL's radiation field was used by Kimel and Elias[12] to show that strong coupling exists between modes. In their terminology, similar to the classic Van der Pol coupled-oscillator analysis, cross-saturation terms between modes were found to be twice

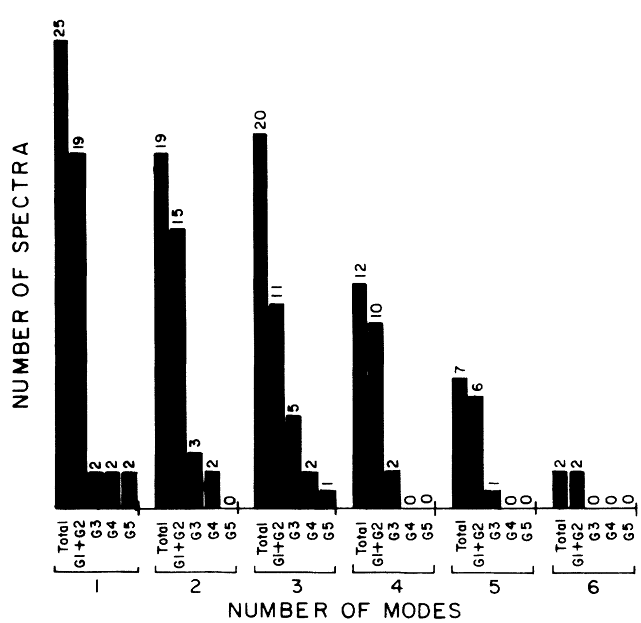

FIG. 4. Statistical distribution of spectra by mode number for the various gate positions.

as strong as self-saturation terms, leading to the prediction that one mode will grow to dominate by suppressing all others. However, this theory does not predict the time required to reach such an equilibrium when many modes are involved.

Antonsen and Levush[4-6] have included large numbers of modes as well as the beam-energy shift characteristics in numerical simulations that more closely approximate the actual FEL experiment. They estimate the time for the onset of coherence in a low-gain, continuous-beam FEL[5] to be $\tau_c \sim \tau_d/\epsilon^2$, where τ_d is the decay time for radiation in the empty cavity and the slippage parameter $\epsilon = (L_u/L_r)(v_g/v_z - 1)$. In this expression, $L_u = N_u\lambda_u$ and v_g is the group velocity of the wave in the interaction region. For the UCSB FEL, these values are $\tau_d \simeq 200$ ns and $\epsilon \simeq 3\times10^{-3}$, respectively, yielding an estimated coherence onset time of $\tau_c \simeq 15$ ms, much longer than the electron-beam pulse. This suggests equilibrium was not reached in this experiment, and the mode distribution was strongly influenced by start-up conditions. Their statistical analysis of the probable distribution of FEL spectra[6] assumes that there is no correlation between the noise driving the complex mode amplitudes, and that each is modeled by a Langevin equation. They arrive at a probability $P_N(F)$ of observing one mode out of a group of N modes to be larger than all others by a factor of F given by

$$P_N(F) = F!/[(N+1)(N+2)\cdots(N+F-1)]$$

(for a fixed detuning $p_{\rm inj}$ centered at $p_{\rm max}$).[13] For $F=2$ and $N=20$ modes, centered about a detuning[13] $\delta p = p_{\rm inj} - p_{\rm max}$ which is itself a random variable uniformly distributed over a range ±0.87, the probability of single-mode spectra is 18%. The range of δp corresponds to pulse-to-pulse energy fluctuations of $\pm0.04\%$. The discrepancy with theory is not large and could be explained by many factors including an overestimation of number of single-mode shots due to the limited bandwidth of the spectrometer and assumptions about the actual start-up conditions. The fraction of observed single-mode shots of course depends both on the criteria for single-mode operation (F parameter) and on the threshold signal above which a peak is counted in the analysis.

An important observation is that the envelope of the FEL power as measured by the Schottky-diode detector showed only a very small degree of modulation [Fig. 2(a)] despite the excitation of multiple longitudinal modes. This is a manifestation of the mode-locking effect and, to our knowledge, has not been previously observed in any oscillator experiment. Interpretation of a weakly modulated power envelope of the FEL output, as an indication of single-mode operation, is therefore not justified.

In conclusion, we have carried out a direct spectral measurement of the output of the UCSB FEL. Multimode and also predominantly single-mode spectra are observed with excitation of two or fewer modes occurring on more than half of the recorded spectra. Predictions of the probability distribution of spectra are in rough agreement with theoretical models.

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