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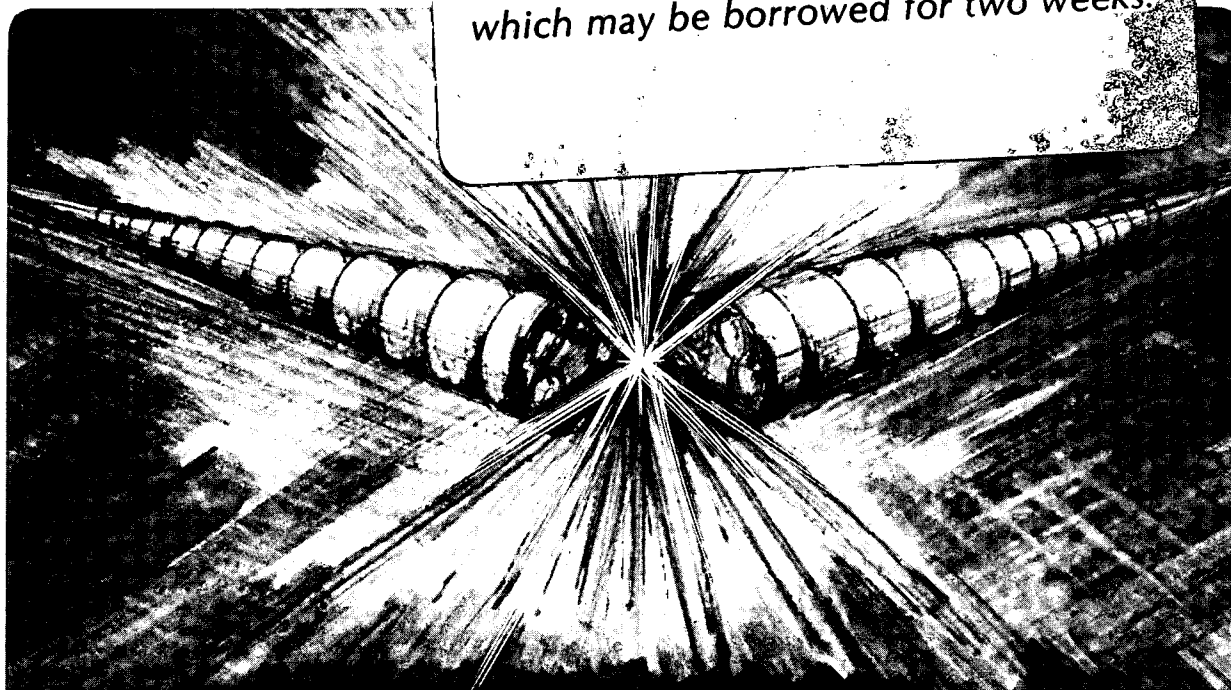
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SIDE BAND CONTROL IN A MILLIMETER WAVE FREE ELECTRON LASER

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ABSTRACT

The frequency offset of the sideband instability in a free electron laser (FEL) should depend on $(1 - v_{\parallel}/v_g)^{-1}$, where $v_{\parallel}$ is the average longitudinal velocity of the electrons and v_g is the group velocity of the electromagnetic waves. In the microwave regime, the group velocity can be controlled by proper choice of the waveguide for the electromagnetic radiation. An experiment has been performed to test the $v_{\parallel}/v_g$ dependence of the sideband shift, employing an FEL operating in the Raman regime with a 700 keV electron beam. At a radiation wavelength of 2.5 mm and undulator wavelength of 1.45 cm in a cylindrical waveguide of radius 6 mm, the sideband offset was observed to be 6% of the fundamental frequency. When the undulator wavelength was changed to 1.85 cm, the radiation wavelength changed to 2.75 mm and the sideband shift increased to 40%, in approximate agreement with the theory.

PACS numbers: 42.55.Tb, 52.75.Ms, 52.70.Gw

Free electron lasers (FEL), especially in the (3 cm - 1 mm) microwave range have been demonstrated to be prodigious sources of power. Microwave FEL experiments at Columbia,¹ MIT,² NRL^{3,4} and LLNL/LBL^{5,6} have reported peak output powers ranging from 2 MW to 1 GW. Only a few studies have been made of the spectral quality of this power, sometimes initiated from noise, and sometimes as an amplification of an input signal.

Many applications of microwave FEL's require a signal with a well-defined frequency; i.e. considerable temporal coherence. The sideband instability threatens this coherence, and is a subject of much FEL work, both experimental^{1,7} and theoretical.⁸

The physical origin of the sideband instability is the slippage between the light pulse and the electron pulse in an FEL. The slippage is customarily considered to occur because the light travels at c , while the electrons travel at some $v_{||} < c$. The slippage couples different longitudinal slices of the electron beam, and can lead to growing modulations in the light intensity, coupled to synchrotron oscillations of electrons in buckets.

A microwave FEL must operate in a waveguide because the wavelength of the electromagnetic radiation is long and diffraction is very strong. But a waveguide provides the possibility of controlling the group velocity of the radiation, or the velocity at which modulations propagate. It is perfectly possible to arrange for the microwave group velocity to equal the parallel electron velocity. In that circumstance, the slippage vanishes, modulations of the radiation do not propagate forward with respect to the electron pulse, and in principle, the sideband instability should be completely stabilized.⁹

For a waveguide we may write

$$\frac{\omega^2}{c^2} = k^2 + k_{\perp}^2, \quad (1)$$

where $k_{\perp}$ is the transverse wave number. The group velocity is

$$v_g \equiv \frac{d\omega}{dk} = \frac{kc^2}{\omega} = c \left[1 + k_{\perp}^2/k^2 \right]^{-1/2}. \quad (2)$$

For large γ , the parallel velocity of the electrons is

$$v_{\parallel} = c \left[1 - \frac{(1+a_w^2)}{2\gamma^2} \right], \quad (3)$$

where a_w is the dimensionless r.m.s. vector potential of the wiggler.

Equating v_g and $v_{\parallel}$ we obtain the condition for no sidebands:

$$\gamma \approx (1 + a_w^2)^{1/2} \left(\frac{k}{k_{\perp}} \right). \quad (4)$$

It is easy to estimate the frequency, in the laboratory, of the sideband as a function of $v_{\parallel}$ and v_g . The sidebands approximately satisfy the relation

$$[(k \pm \Delta k) + k_w]z - (\omega \pm \Delta\omega)t \approx k_{\text{synch}}z, \quad (5)$$

where $\Delta\omega$ and Δk are the shift from the fundamental of the sideband frequency and wavenumber, respectively, and k_{synch} is the wavenumber of the synchrotron oscillations of electrons in the ponderomotive potential or buckets. Writing $z = v_{\parallel}t$, using the resonance condition for the FEL

$$\omega = (k + k_w)v_{\parallel}, \quad (6)$$

and recognizing that $\Delta\omega = v_g \Delta k$, one finds that

$$\Delta\omega \approx \frac{k_{\text{synch}} c}{1 - v_{\parallel}/v_g} \quad (7)$$

This result is also valid if the Raman regime and waveguide effects are included. It is Eq. (7) which we study experimentally. As v_g approaches $v_{\parallel}$ the sideband frequencies should get further from the main frequency.

The equations that describe sideband growth^{10,11} are precisely the standard FEL equations^{12,13} but with derivatives with respect to longitudinal distance z replaced with two different convective derivatives corresponding to the particle motion (in the 2N-particle equations, where $v_{\parallel}$ enters) and to the pulse motion (in the field equations, where v_g enters). The equations have the consequence that the growth rate of the sideband instability is independent of $v_{\parallel}/v_g$. This conclusion cannot be valid as $v_{\parallel} \rightarrow v_g$ because Eq. (7) predicts that the lower sideband moves beyond cutoff; this must have a significant effect upon the sideband growth rate. The difficulty arises because the standard FEL equations, with convective derivatives, consider a slowly varying amplitude and phase of the central frequency with fixed group velocity. This approximation is not adequate to describe sidebands which are far removed (in $\Delta\omega/\omega$ or in $\Delta k/k$) from the central frequency.

The experiment was done with the Columbia University Free Electron Laser, and the reader is referred to reference 1 for further experimental details and a schematic of the laser. An electron beam was extracted from an apertured, cold-cathode diode immersed in a strong (7-10 kG) magnetic field. A typical value of accelerator voltage was ~ 700 kV, and a beam current ~ 200 A was injected down the axis of a 6 mm diameter drift tube which also serves as a cylindrical waveguide. The undulator was a bifilar helical winding energized

by a small capacitor bank timed with the accelerator pulse. The undulator consisted of a uniform section 50 cm in length between two zones (7.3 cm each) of adiabatically changing field. Two mirrors were used for feedback; the upstream mirror was a polished annular disk with reflectivity = 65% and the output mirror was a surface of a quartz window, with net reflectivity ~ 5-10%. After a certain start time, the FEL oscillates at a power level ~ 2-4 MW (determined calorimetrically). The spectrum was observed with a grating spectrometer (resolving power = 100)¹⁴ when the power reached saturation. To obtain each spectrum, roughly 100 shots must be taken under circumstances of constant and reproducible accelerator voltage (2% variation was acceptable), and data at each wavelength was averaged. To speed the data-acquisition, two calibrated Schottky-barrier diode detectors were used in the spectrometer.

The range of wavelength studied was ~ 2-4 mm. The laser operates in the regime of stimulated Raman backscattering, as the beam current density is high (~ 1 kA/cm²) and the pump field is "weak" ($B_1 \sim 600-800$ G); the quiver velocity of the electrons, taking into account the guiding field, is about 10% of the speed of light. The electron orbits are "stable Type I." A 3D theory¹⁷ has been used to successfully predict not only the wavelength of the radiation but also the small-signal coefficient of exponential signal growth (~ 0.1 cm⁻¹). The EM wave in the drift tube is propagated in the TE_{11} mode, appreciably above the cutoff wavelength of 1 cm.

A study of the time-dependent power at the wavelength of the FEL fundamental and its sideband showed the following features. After an interval of a few radiation bounce times ($2L_c/c \sim 10$ nsec each), the power was observed to grow to detectable levels: this defines the start-time of the device.

Roughly one bounce time later the fundamental saturates, and fluctuates in strength at megawatt levels. This is followed, usually within one bounce time, by the appearance of a strong sideband signal. This indicates that the sideband growth rate is comparable to the growth rate of the FEL signal.

The experiment was done in two stages, using different undulators. These were identical in all respects, except that the period (λ_u) in one case was 1.45 cm (corresponding to the experimental situation of reference 1) while the other undulator had period of 1.85 cm. In Fig. 1 is shown spectrum obtained with the $\lambda_u = 1.45$ cm undulator (another spectrum, at weaker $B_{\perp}$, is shown as Fig. 1c in reference 1). In Fig. 1 the spectrum shows both upper and lower sidebands; at stronger pump field, the long wavelength sideband grows to a power level comparable with that of the fundamental. The line width of the fundamental, under conditions where the sideband power is not large,¹ is about 1%. On the other hand, the width of the linear growth spectrum is theoretically found to be $\sim 5-10\%$, so appreciable line-narrowing has occurred from the quasi-optical resonator ($Q \sim 1000$). From Eq. (7), the fractional sideband shift is proportional to the ratio N_{sy}/N , where N , the number of undulator periods, is 35. The synchrotron period, L_{sy} , defines $N_{sy} = L/L_{sy}$, where L is the undulator length. The synchrotron period can be calculated once the power level in the resonator is known; this gives $N_{sy} \sim 1$. With $V = 700$ kV, at the given B , $v_{\parallel}/c = 0.90$ and we compute $v_{\parallel}/v_g = 0.93$ from the waveguide properties; the predicted (Eq. 7) sideband shift is 6%, in good agreement with the measured value.

The experiment was then "repeated" at $V = 780$ kV, using the same hardware, but replacing the 1.45 cm period undulator with the 1.85 cm undulator. This

has the effect of increasing the fundamental wavelength in which case the ratio $v_{||}/v_g$ becomes a very important factor in increasing the sideband shift. In order to keep the Group I orbits away from magneto-resonance, we reduced the guiding field from 9.5 to 7.3 kG. In Fig. 2 the spectrum clearly shows the FEL line at 2.75 mm and the lower sideband at 4 mm; the most striking feature is the increase of the sideband shift to $\sim 40\%$ (the upper sideband fell outside the range of the spectrometer grating). Computing $v_{||}/c = 0.91$, noting that now $N = 27$, and taking $N_{sy} = 1$ (the laser power is nearly the same), we find, from Eq. (7), $v_{||}/v_g = 0.98$. As the cutoff wavelength has not changed, we can calculate what FEL wavelength would be required to give this group velocity: the result is 3 mm, which is close to the actual FEL fundamental. The spectrum of Fig. 2 shows a dramatic increase of the sideband shift due to a small change in group velocity, in accord with the result Eq. (7).

Calculation of the small-signal growth rate have been made for the conditions appropriate for Figs. 1,2, using a 3D theory;¹⁵ these are shown as dotted lines in the figures (the peak growth rate is kept about the same). It is interesting to note that the sideband falls outside the zone of unstable growth for the FEL in the case of the 1.85 cm undulator. Although the effect of the guiding field is accounted for in the small signal theory, it is not accounted for by the theory in this paper, nor has it been used in the waveguide calculations. The waveguide is filled with electrons through which a right-handed circularly-polarized EM wave is propagated, but the effect of the guiding field on the group velocity is negligible because the invariant plasma frequency $[4\pi ne^2/\gamma m]^{1/2}$ is ~ 2 GHz and the cyclotron frequency $eB/\gamma mc$ is ~ 9 GHz, whereas the wave frequency is 75-100 GHz.

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Figure Captions

- Fig. 1 Spectrum of FEL radiation, obtained under conditions: $V = 700$ kV;
 $B_{\perp} = 760$ G, $I = 200$ A, $\lambda_u = 1.45$ cm. The theory curve (dotted line)
is the small signal growth rate calculated according to reference 17.
The solid line is drawn through the data points with a spline fit.
The spectrum is obtained under conditions of saturated power.
Guiding field = 9.5 kG.
- Fig. 2 Data obtained for the same FEL, but the following conditions:
 $V = 780$ kV, $B_{\perp} = 690$ G, $\lambda_u = 1.85$ cm, and guiding field = 7.3 kG.

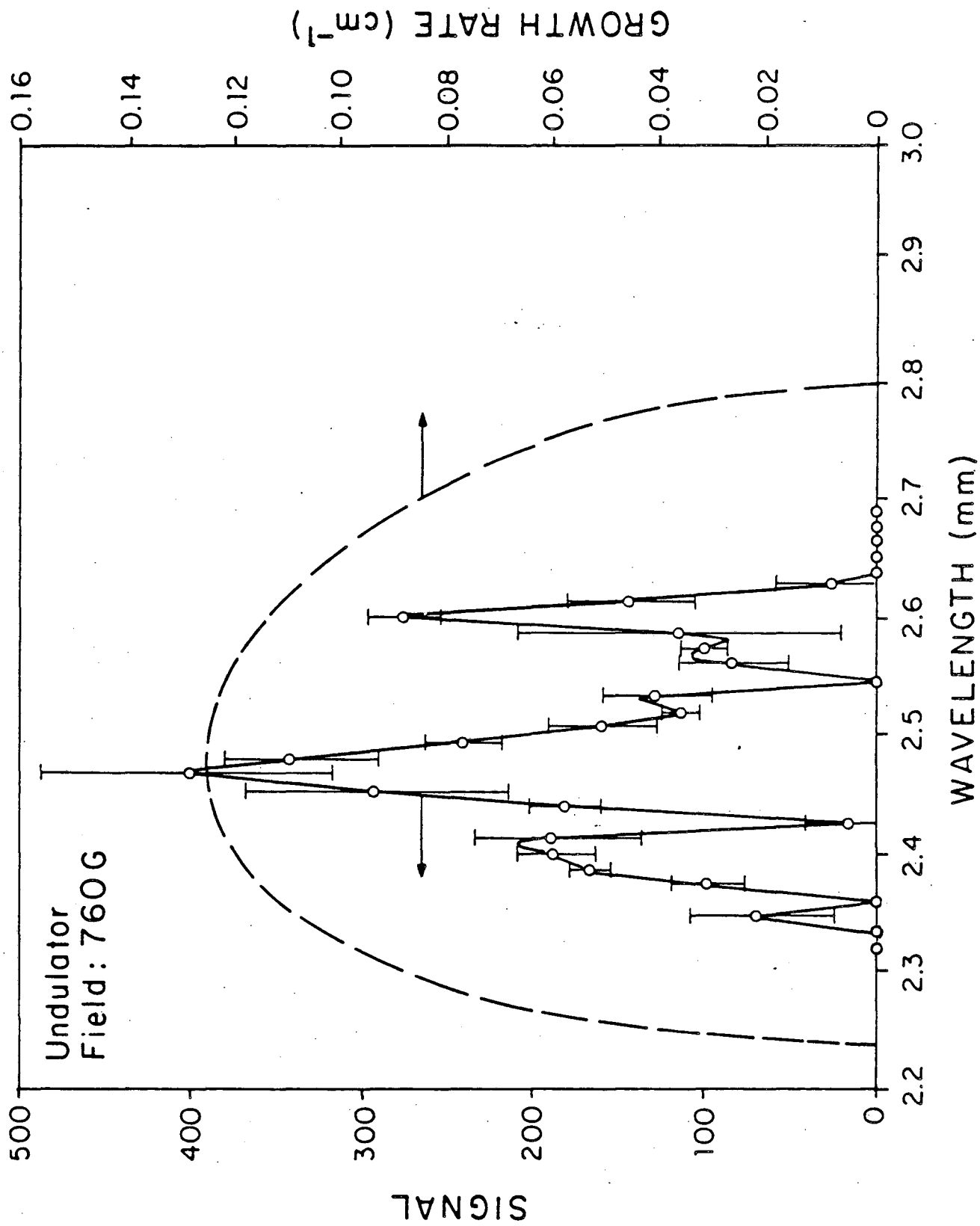


Fig. 1

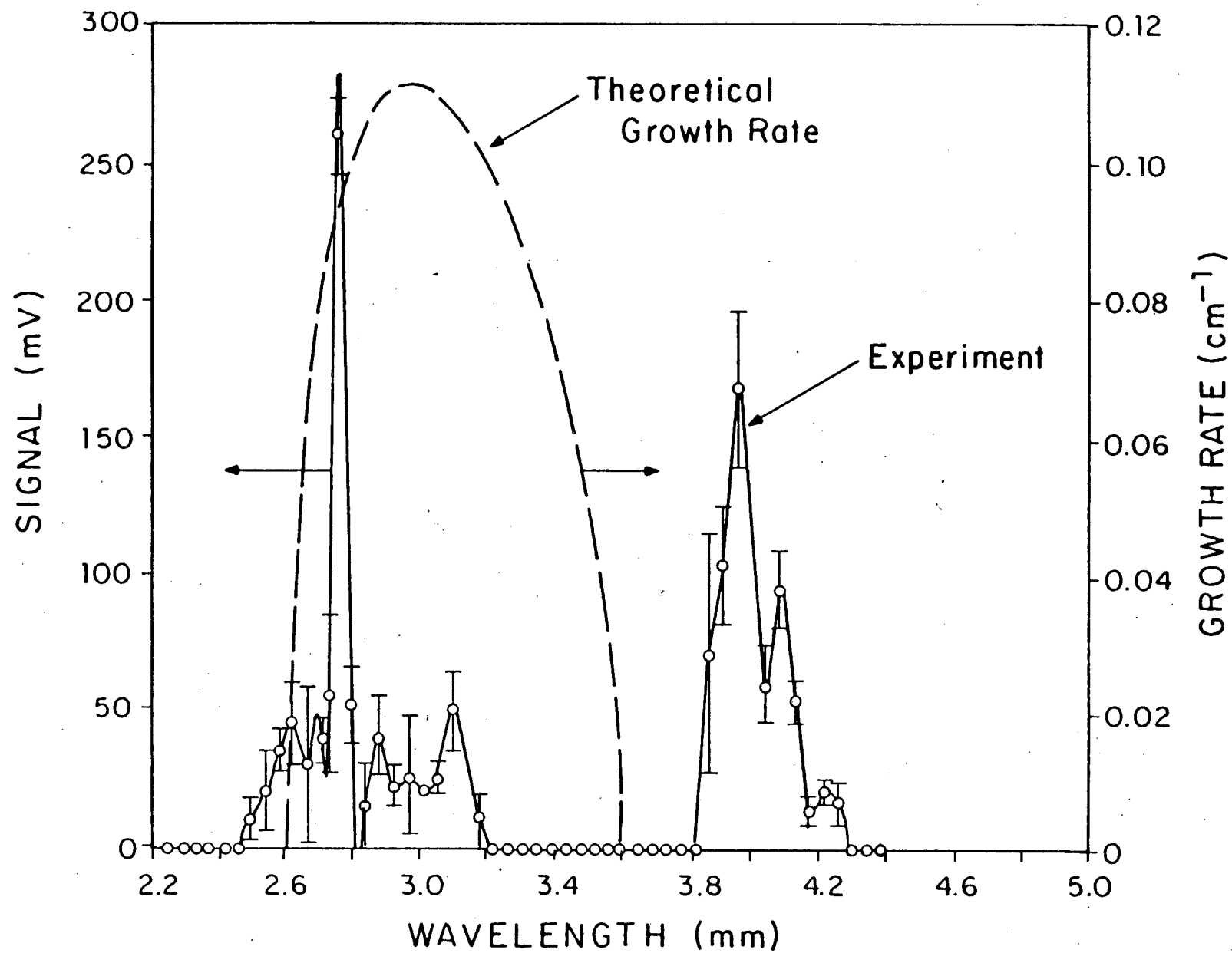


Fig. 2

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