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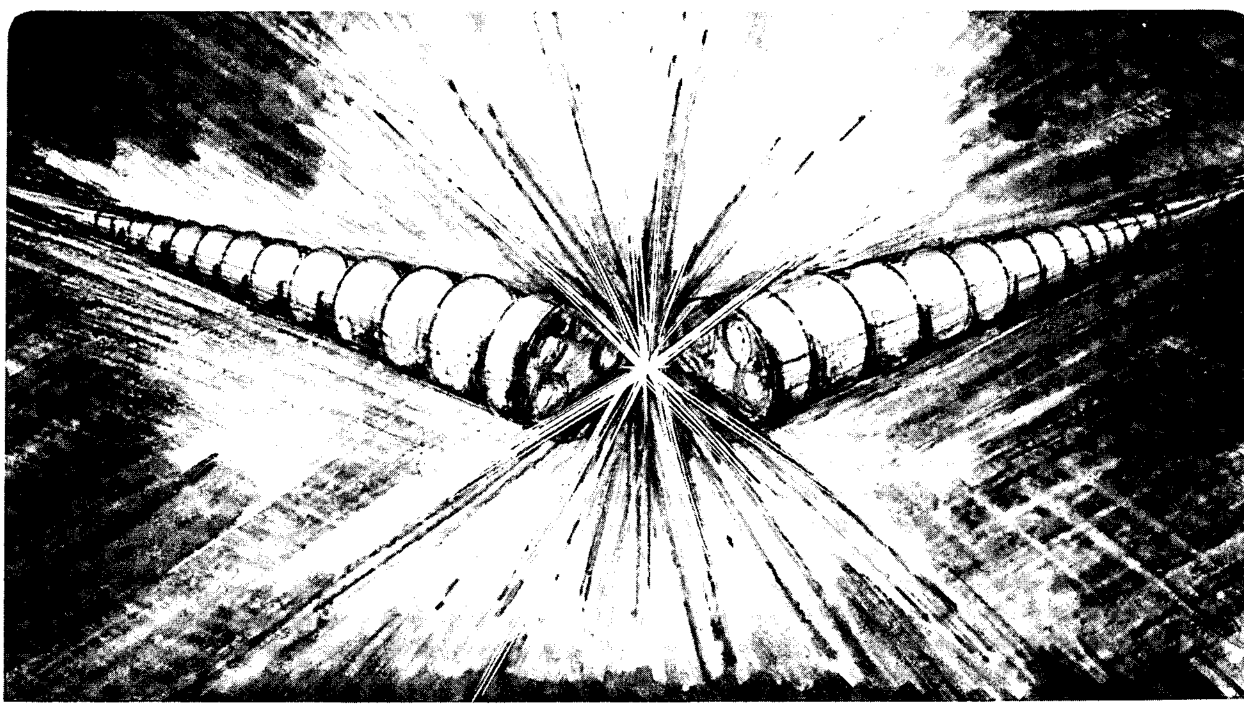

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Time-resolved study of sideband generation and transition to chaos on an infrared FEL*

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We report observations on sideband generation and transition to chaos in an infrared Free Electron Laser operating at a wavelength λ_r of 4 μm with a low loss optical cavity. The temporal evolution of the radiation spectrum through the complete macropulse has been measured on a micropulse to micropulse basis [1]. Stable sidebands are observed for small cavity detuning with frequency offsets in good agreement with calculations. For even smaller cavity detuning, self-oscillations occur with the main laser wavelength varying by up to 2 %. Using a wavelength stabilization system based on RF feedback [2], we have suppressed these wavelength fluctuations without loss of peak power.

1. Introduction

Free electron lasers operating in a high power regime can be unstable to trapped particle instabilities when slippage between the light pulse and the electron bunch causes different longitudinal slices of the electron bunch to be coupled. In the sideband instability [3], large optical wave amplitudes will cause the electron bunch to undergo synchrotron oscillations in phase space during its passage through the undulator. Simulations as well as time-integrated experiments [4] indicate that radiation spectra can exhibit a narrow spectral sideband at relatively low power operation or very complex

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broad band spectra at high power operation. Theoretical studies [5] have furthermore indicated that FELs can evolve from regular towards chaotic behavior via a period doubling cascade, intermittency and quasi-periodicity.

To study the dynamical behavior of the instability we have developed a diagnostic system [1] capable of measuring the spectrum of every single micropulse in a macropulse with a duration long compared to the growth time of the instability. Using this diagnostic system we have obtained the first time-resolved radiation spectra from an infrared FEL for a cavity detuning parameter D ($= \delta L/\lambda_r$) ranging between -0.5 and 0.2. Here δL is the change in cavity length from perfect synchronism. Micropulse spectra have been obtained for FELs operating in the visible wavelength range by the use of optical streak cameras [6] and for near infrared FELs [7] (<1.8 μm) by the use of high digitizing speed array systems.

In addition, we have performed a time-resolved measurement demonstrating suppression of the wavelength instability through modulation of the electron beam energy. Although the sideband instability can lead to enhanced extraction efficiency for uniform wigglers, the consequential reduction in the temporal coherence often makes this mode of operation undesirable. With the exception of group velocity control [8], most sideband suppression techniques [9] such as cavity detuning, and wavelength dependent cavity loss invariably have led to reduced FEL efficiency.

2. Experimental setup and parameters

The experiment used the Stanford SCA/FEL operating at $\lambda_r = 4.08$ μm with a measured optical cavity Q of 229. The wiggler used in this experiment had 120 periods (N_w), a period $\lambda_w = 3.6$ cm, and an RMS normalized wiggler strength $a_w = 0.7$. The linac produced 1.8 - 2.0 ms long macropulses at 10 Hz, containing electron bunches at a repetition frequency of 11.8 MHz and a bunch duration on the order of 1 - 4 ps. The peak current was on the order of 5 A. As a function of optical cavity detuning, the optical pulses, repeating also at 11.8 MHz, had a measured duration of 1.5 - 3.4 ps and a pulse energy of 0.05 - 0.2 μJ. The average output power for various cavity detuning lengths ranged between 0.5 - 1.5 W resulting in an average intracavity power on the order of 240 - 730 W.

The SCA/FEL feedback system allows stabilization of the FEL wavelength through changes in the electron beam energy. The time scale for changes in the electron beam energy is 6 - 12 μs [10], much faster than the cavity life time of 190 μs in this experiment. The measured bandwidth of the feedback is on the order of 10 kHz. The wavelength is monitored using a two-element detector at the output of a spectrometer; the output is then used to modulate the energy of one of the accelerating structures so as to correct for any wavelength drift.

The spectral diagnostic, which consists of a 1 m focal length spectrometer with a 150 grooves/mm grating and a previously described image dissector readout system [1], had a measured spectral resolution of 5 nm/bin [10] and a spectral coverage range of 100 nm (20 bins), equivalent to 2.5 % of λ_r. A bin refers to a slice of the spectrum.

3. Sidebands and chaotic transition

In Fig. 1 we show the FEL peak output power as a function of normalized cavity detuning D. We have adopted D = 0 as the cavity length resulting in maximum peak output power without wavelength stabilization.

Fig. 2 displays time-resolved FEL spectra for four different cavity detuning lengths without wavelength stabilization. The initial wavelength chirp from longer wavelengths towards shorter wavelengths is somewhat surprising but is believed to be due to an electron beam energy change in the beginning of the macropulse. It is important to note that the present diagnostic does not have enough dynamic range or sensitivity to measure the transition from initial start up, seeded by spontaneous emission, to saturation with an expected red shifting of the wavelength. For D = -0.41 (Fig. 2b), a sideband is seen to grow after saturation of the main frequency, separated from the fundamental by 0.98 ± 0.06 %. The sideband saturates in typically 10 - 20 μs, i.e. 100 to 200 passes. The theoretical side band frequency is given by [8]

$$\Delta\omega = \frac{ck_{synch}}{1 - \frac{v_{||}}{v_g}} = \frac{c\sqrt{2k_w k_r a_w a_r}}{\gamma_r}\frac{\lambda_w}{\lambda_r} \qquad (1).$$

Here k_{synch} is the synchrotron wavenumber, $v_{||}$ the longitudinal electron velocity, v_g the group velocity of the light pulse, k_w and k_r the wavenumbers of the wiggler and the FEL radiation light respectively, a_w and a_r the normalized wiggler and radiation vector potential respectively, and c the speed of light in vacuum. Using the measured average macropulse power level of 0.43 - 1.5 W, Eqn. 1 predicts $\Delta\omega/\omega$ = 0.93 - 1.02 %, in good agreement with measurements.

For even smaller detuning (D = -0.36), periodic self-oscillations are seen in the wavelength (Fig. 2 c) as well as the output power (Fig. 3). The typical oscillation frequency observed in our experiment varies in the range of 1 - 25 kHz. Although we cannot rule out cavity length changes due to mirror vibrations or fluctuations in the electron beam parameters as the cause of these fluctuations, similar limit cycle behavior, characterized by such periodic oscillations, has recently also been observed in the FELIX experiment [11]. The observed periodicity is in reasonable agreement with an estimate for the limit cycle oscillation frequency given by [5]

$$f = f_c \frac{L_{syn}}{2|\delta L|} \qquad (2)$$

Here f_c is the cavity frequency (11.8 MHz), L_{syn} the slippage distance in a synchrotron period and δL the cavity length detuning.

For an even longer optical cavity, the main frequency varies more widely over the 2.5 % wide spectral range of the diagnostic (Fig. 2 d). Whether this behavior is chaotic cannot be definitively answered because the macropulse length is too short to follow the spectrum over many oscillation periods. However, in a preliminary attempt to catalogue the behavior, we next estimate various branching parameters and compare with calculations of chaotic FEL behavior by Hahn et al. [5]. The branching parameters of interest are the slippage parameter S ($=L_s/L_e$) and the scaled synchrotron slippage distance μ ($=L_s/L_{syn}$). Here L_e is the electron bunch length and L_s the usual slippage length. For our experiment, S = 0.74 - 0.85, μ = 1.12 - 1.43 and D = -0.12 - 0.02 are ranges for the branching parameters where stochastic behavior has been observed. For a higher gain system, allowing longer detuning lengths (D = -2.0), simulations by Hahn et al. [5] indicate that routes to chaos via quasi-periodicity and intermittency exist for identical μ and S parameter ranges.

4. Instability suppression using RF feedback system

Fig. 4 shows the dramatic change in spectrum for the same cavity detuning with the RF feedback off and on. Wavelength drift as well as power fluctuations are greatly suppressed. We also note that the output power with RF feedback on is about equal to the maximum output power (Fig. 1).

The details of the instability suppression depend upon the FEL operation regime: either narrow band sideband generation (Fig. 2b) or center wavelength drift (Figs. 2d, 4a). Whereas the latter case is intuitively simpler to understand, the former case depends on the wavelength coverage of the wavelength monitor since in this case (low power) the center wavelength does not shift. Provided the two-element detector of the feedback loop covers more than a 1 % wavelength interval, it will sense the centroid of the spectrum shifting towards longer wavelength as soon as a sideband grows. This then causes an increase in beam energy as compensation. In Fig 2b it can be seen that a change in center wavelength does indeed lead to suppression of the sideband. We are currently carrying out detailed simulations to further study the details and potential of this technique and plan to report on our findings in a subsequent paper.

5. Acknowledgments

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Figure 1: FEL peak output power as a function of normalized cavity detuning D with (circles) and without (dots) RF feedback. We have adopted D = 0 as the cavity length resulting in maximum output power without RF feedback. The line through the data connects average power levels for each detuning.

Figure 2: Measured FEL spectrum as a function of time for D = -0.47 (a), D = -0.41 (b), D = -0.36 (c), and D = -0.27 (d).

Figure 3: Output power as a function of time for case c in Fig. 2. The self-oscillation which lasts about 700 μs has a frequency on the order of 10 kHz.

Figure 4: Measured FELspectrum as a function of time for D = 0.065 without (a) and with (b) RF feedback wavelength stabilization.

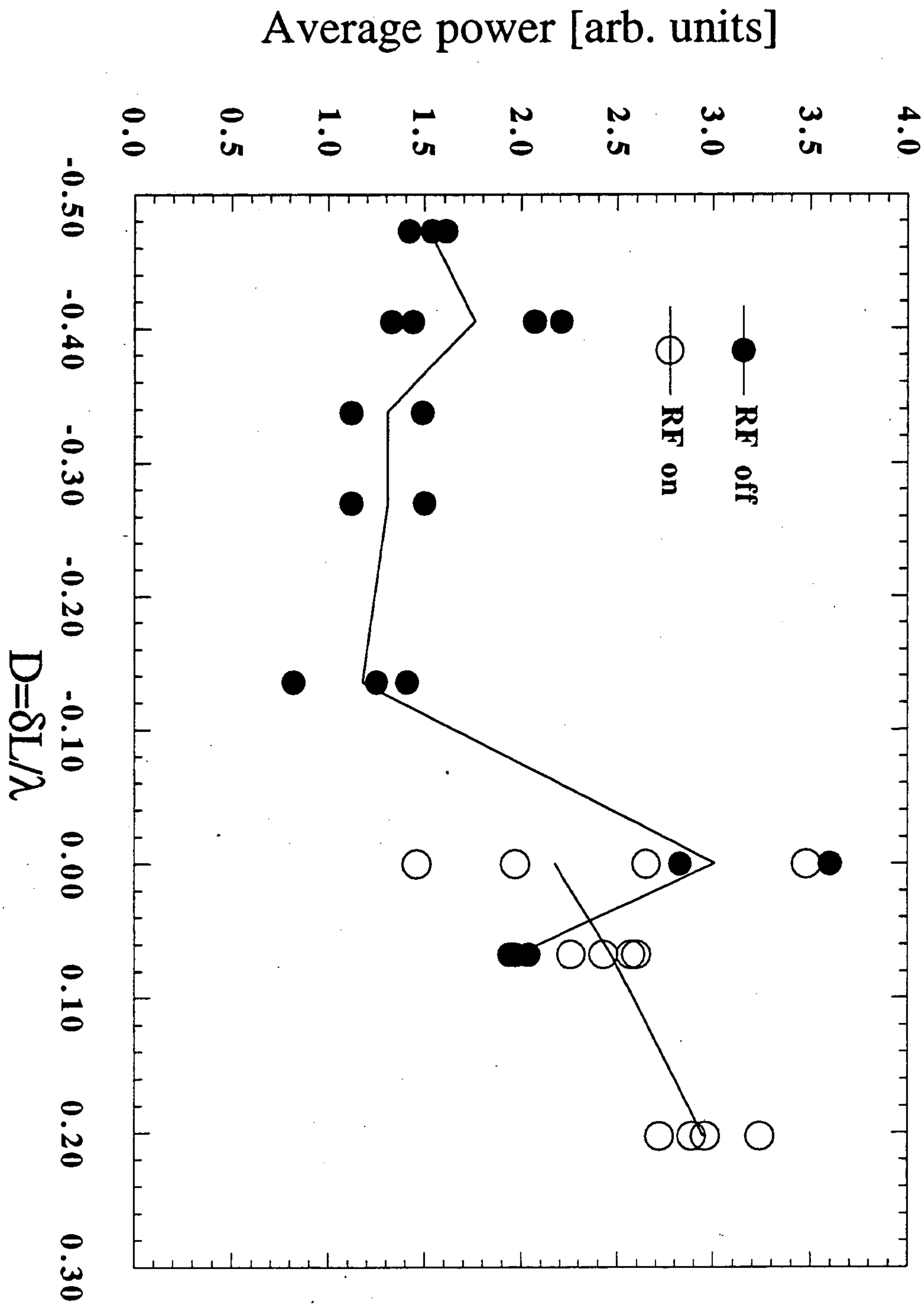

Average power [arb. units]
D=δL/λ
RF off
RF on
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30

Figure 1

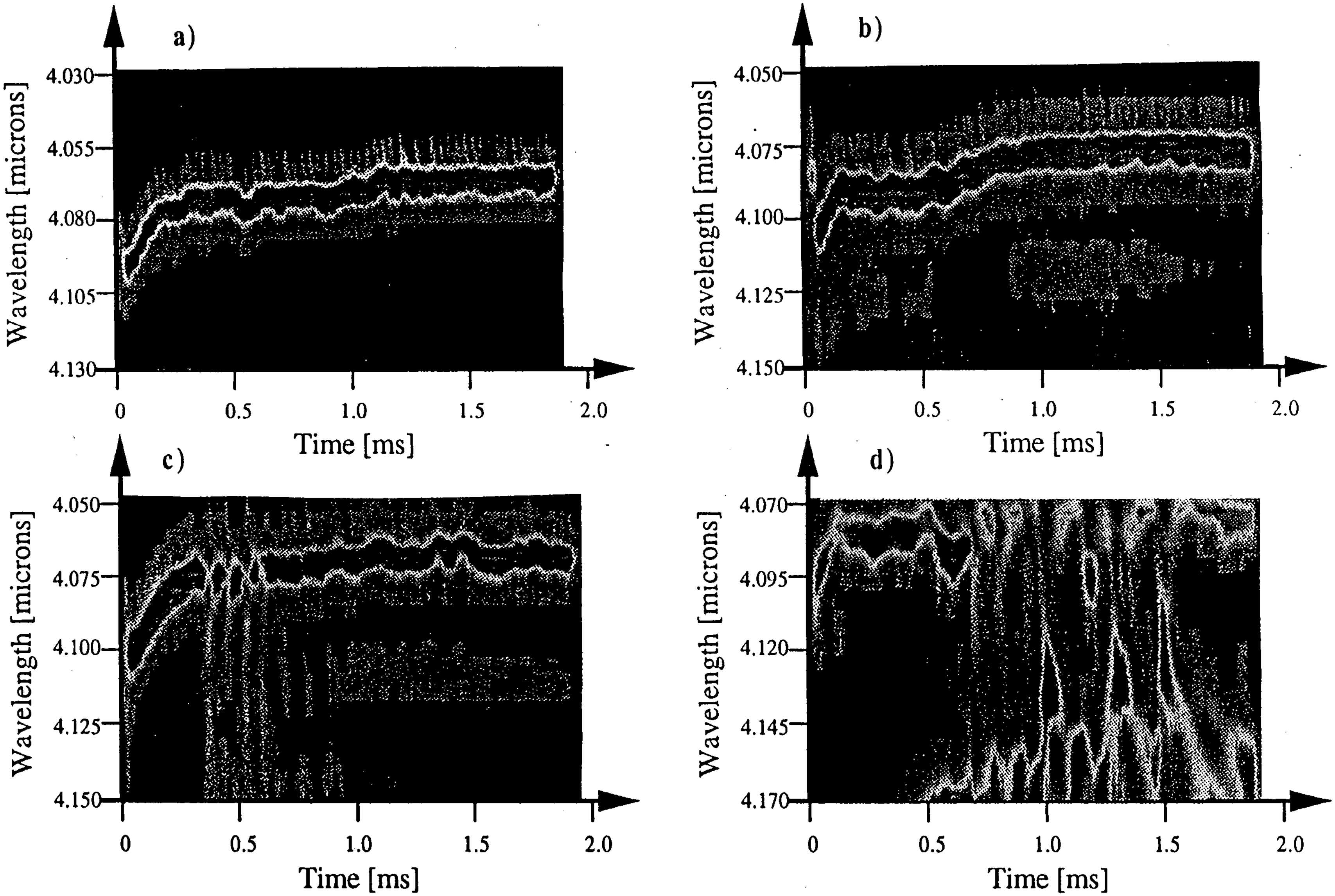
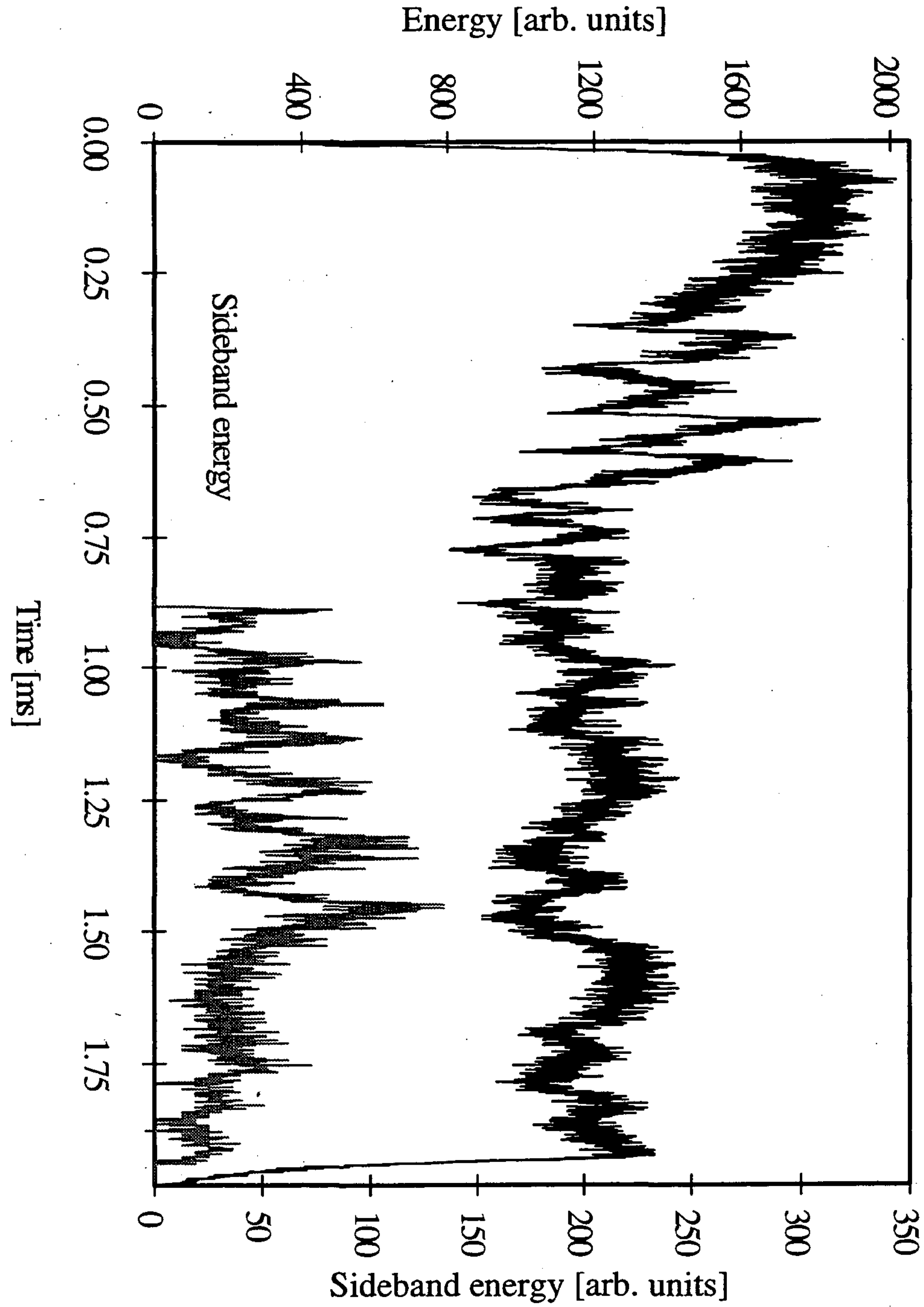
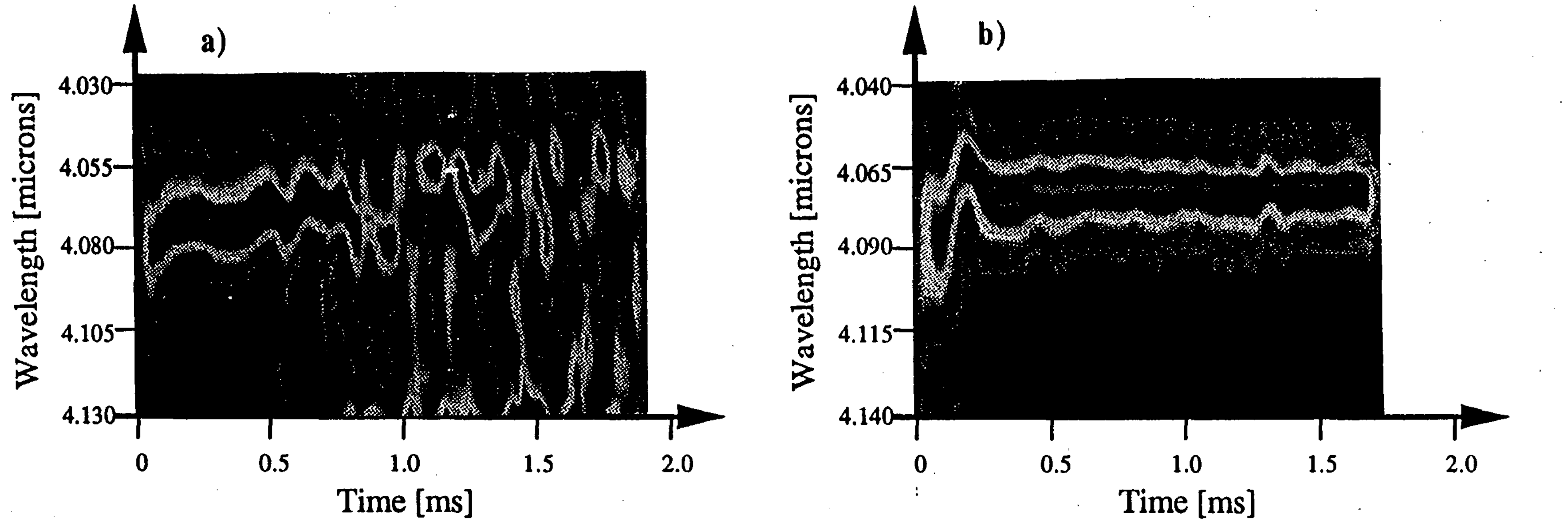

a)
4.030
4.055
4.080
4.105
4.130
Wavelength [microns]
0
0.5
1.0
1.5
2.0
Time [ms]
b)
4.050
4.075
4.100
4.125
4.150
Wavelength [microns]
0
0.5
1.0
1.5
2.0
Time [ms]
c)
4.050
4.075
4.100
4.125
4.150
Wavelength [microns]
0
0.5
1.0
1.5
2.0
Time [ms]
d)
4.070
4.095
4.120
4.145
4.170
Wavelength [microns]
0
0.5
1.0
1.5
2.0
Time [ms]

Figure 2



Energy [arb. units]
0
400
800
1200
1600
2000
Sideband energy
Time [ms]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
0
50
100
150
200
250
300
350
Sideband energy [arb. units]

Figure 3



a)
Wavelength [microns]
4.030
4.055
4.080
4.105
4.130
0
0.5
1.0
1.5
2.0
Time [ms]
b)
Wavelength [microns]
4.040
4.065
4.090
4.115
4.140
0
0.5
1.0
1.5
2.0
Time [ms]

Figure 4

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