New Folder Name Apparent Relaxation Oscillations

Apparent relaxation oscillations in the frequency noise of a diode-pumped miniature Nd:YAG ring laser

A M Campbell, S Rowan, J Hough
Department of Physics and Astronomy,
University of Glasgow, Glasgow G12 8QQ,
Scotland, UK

Abstract

We have set an upper limit to apparent relaxation oscillations in the frequency noise of a diode-pumped single-mode monolithic Nd:YAG ring laser using an RF reflection locking technique, and have observed the effect on the frequency noise spectrum of a servo system which damps relaxation oscillations as observed in intensity noise.

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1. Introduction

The development of a high power stable continuous wave Nd:YAG laser operated at its fundamental wavelength of 1064 nm, or frequency doubled to 532 nm, is of great interest for use in the next generation of gravitational wave detectors [1]. Diode-pumped monolithic Nd:YAG ring lasers, which show very low noise characteristics at low frequencies [2], could be ideal candidates for seeding such a high power cw Nd:YAG laser. However, above about 100 kHz, relaxation oscillations produce intensity noise in these lasers. Although the relaxation oscillation frequencies are well above the frequencies of interest for gravitational wave detectors (< 100 Hz to a few kHz), large fluctuations in intensity or frequency at these frequencies could couple into measurements at lower frequencies through nonlinearities in the detection system.

Relaxation oscillations observed in the intensity noise of Nd:YAG lasers are well known, and it is relatively easy to damp them in diode pumped lasers by servo controlling the diode current [3]. However, as far as we are aware, there is only one report in the literature frequency noise at relaxation oscillation frequencies [4] in Nd:YAG lasers. This was for the 1320 nm transition in a diode-pumped Nd:YAG rod laser. These measurements gave an upper limit to frequency noise of about 200 Hz/√Hz due to a peak at the relaxation oscillation frequency. It is important to have a more accurate measure of this noise for miniature diode-pumped ring lasers.

In the following paper we present our results of the measurement of frequency noise at the relaxation oscillation frequency in a miniature Nd:YAG ring laser, and of the effect on this noise of a servo system used to damp relaxation oscillations in the intensity noise.

2. Experimental system

The laser we used was a monolithic diode-pumped miniature Nd:YAG ring laser built at the Laser Zentrum in Hannover, Germany, based on the original design by Kane and Byer [5]. This laser emits up to 400 mW in the TEM_{00} mode, but for measurements made here was run at 200 mW.

To measure frequency noise we used a Fabry-Perot cavity of linewidth 15 MHz as a discriminator. The resonant frequency of the cavity was servo controlled to the frequency of the laser at low frequencies (< 1kHz) using RF reflection locking [6] and the error point of the system was used to allow measurement of frequency noise at high frequencies. The RF reflection locking technique provides a high degree of rejection of cross-coupling of intensity noise into the frequency noise signal provided that the cavity is locked at the centre of its resonance.

The experimental apparatus is shown in Figure 1. Light from the laser, after isolation by a Faraday effect device, is passed through a half wave plate to rotate the polarisation to the correct direction for the electro-optic modulator which phase modulates the light at 10 MHz for the RF reflection locking. Some light is split off for a servo which may be used to damp the relaxation oscillations as observed in the intensity noise spectrum (this is discussed in the Appendix), and some light goes to a monitor photodiode. The fraction of the light used to make frequency noise measurements is mode-matched into the Fabry-Perot discriminating cavity using two lenses; the visibility was about 0.8. The polarising beam splitter and quarter wave plate allow the light reflected from the cavity to be directed onto a photodiode and amplifier tuned to the RF modulation frequency and to another monitor photodiode. The signal from the photodiode and amplifier is amplified, coherently demodulated at the mixer, filtered and fed back to a piezo-electric device on which one of the cavity mirrors is mounted. Thi ensures the resonant frequency of the cavity remains locked to the frequency of the laser over a bandwidth of about 1 kHz. Measurements of noise at hundreds of kHz are made at the error point of the system, directly after the mixer. Included in the feedback is a parallel path to boost the dc and low frequency gain, and a facility for adding in a small amount of dc to adjust for any offset of the locking point caused by RF pickup or by spurious amplitude modulation of the light at 10 MHz by the electro-optic modulator. The other side of the PZT is connected to a battery driven variable dc supply to allow coarse adjustment of the cavity resonant frequency so that lock can be achieved.

3. Results

We made two sets of measurements on this laser, one with better sensitivity; but both sets of results are of interest and will be discussed.

3.1. First Measurement

The first measurement is shown in Figure 2. This is a spectrum of the frequency noise measured using a Hewlett Packard 8590A RF spectrum analyser. An instrumental peak at 0 Hz is at the centre of the screen and one half of the screen is essentially a mirror image of the other. The full screen span is 750 kHz: the region of interest spans 375 kHz. The peak at 250 kHz is at the relaxation oscillation frequency: this peak represents an upper limit on the apparent frequency noise due to relaxation oscillations and we calibrated its level to be about 7 Hz/√Hz from measurement of the slope of the discriminator curve of the cavity. The fractional intensity noise at this frequency is about $10^{-5}/\sqrt{\text{Hz}}$. The other peak at 120 kHz is due to an intensity modulation signal imposed by us on the laser by modulating the diode pump current at the diode driver input. This signal allowed us to minimise sensitivity to intensity noise in the system by adjusting the dc offset in the servo loop.

An interesting effect was observed when the dc offset in the servo loop was adjusted to either side of the value which minimised the applied 120 kHz intensity modulated signal. Figure 3 shows the relative size of the two peaks (intensity modulation and relaxation oscillation) when the dc offset was adjusted to increase the applied intensity peak by about 10 dB on either side of its minimum value. The peak associated with the relaxation oscillations did not increase by the same amount in the two cases, the difference in heights between the relaxation oscillation peak and the applied peak being about 7 dB on one side, and about 3 dB on the other side. This suggests that there is some difference in the type of noise associated with the applied intensity peak and with the relaxation oscillation peak. Consistent with this finding is the fact that different values of dc offset were required to minimise the relaxation oscillation peak and the applied intensity peak.

From the above measurements it seems likely that either the applied intensity peak or the relaxation oscillation peak is at least partly due to frequency noise or beam geometry fluctuations (which can couple into the observed frequency noise spectrum). In order to investigate the situation further we observed the effect of actively damping the relaxation oscillations as observed in intensity noise. The feedback signal from the servo system was applied to the diode pump current driver, where previously we had applied our intensity peak. (A diagram of this servo system and its Nyquist plot is shown in Figure 4 and is discussed in the Appendix.) We observed the intensity and the frequency noise spectra simultaneously as the intensity servo was turned on. The relaxation oscillation reduced in exactly the same way in both spectra: a 10 dB reduction in the relaxation oscillation peak in the intensity noise spectrum corresponded to a 10 dB reduction in the relaxation oscillation peak in the frequency noise spectrum. If the signal at the input to the diode driver caused anything other than intensity noise in the laser light (for instance frequency noise or beam geometry fluctuations) we would not expect such a simple relationship. We therefore draw the following three conclusions as the most likely explanation of these observations:

— a signal applied to the diode current driver does produce intensity modulation with few, if any, side effects. Hence the 120 kHz peak, produced by a signal applied to the diode current driver, as observed in the frequency noise measurement system, is indeed caused by intensity noise in the laser;

— the peak in the frequency noise spectrum associated with the relaxation oscillations is partly due to frequency noise or beam geometry fluctuations in addition to some intensity noise;

— fluctuations in frequency or beam geometry associated with the relaxation oscillations are reduced by the feedback system used to damp the relaxation oscillations observed in intensity noise.

3.2.Second Measurement

We repeated the measurements in order to investigate our findings more fully at improved sensitivity. We cleaned and re-aligned the optics (in particular we re-aligned the beam through the electro-optic modulator). We operated with a mode-matching which gave a visibility of 0.8, and with a modulation index of 0.24. These experiments gave us an improved measurement of the level of the apparent frequency noise due to relaxation oscillations, this being about 1 Hz/√Hz at 250 kHz. The measurement floor was about 0.4 Hz√Hz of which about 0.2 Hz/√Hz was photon shot noise. This measurement is shown in Figure 5a, where the applied peak is also shown at a frequency of 180 kHz.

In this case, however, both the applied intensity peak and the peak due to relaxation oscillations minimised at the same value of dc offset in the cavity servo loop, and when we altered the dc offset on either side of the value that minimised the peaks, we could discern no difference in the relative size of the applied peak and the peak due to relaxation oscillations at the two values of dc offset. We conclude from this that our first measurements were probably affected by beam geometry fluctuations introduced by imperfect alignment of the beam through the electro-optic modulator. Beam geometry fluctuations caused by relaxation oscillations would have imposed intensity modulation of the beam at 10 MHz, modulated at the relaxation oscillation frequency and thus would appear on the demodulated signal: this would not have been the case for the applied peak which was purely an intensity signal. When we re-aligned the beam we reduced the sensitivity of our measurement system to beam geometry fluctuations. The apparent residual relaxation oscillations in the frequency noise spectrum in the improved measurement are likely to be caused by intensity noise, since both the applied peak and the peak at the relaxation oscillation frequency behave in exactly the same way. High frequency intensity noise coupled into the measured frequency spectrum because of small deviations of the servo locking point from the centre of the cavity resonance. These deviations occurred at a few kHz, outside the bandwidth of the servo.

When we applied the servo to damp relaxation oscillations in intensity noise, the relaxation oscillations were damped in both the intensity noise spectrum and the frequency noise spectrum (Figures 5b and 6a and b). The applied peak was slightly increased in each spectrum because the servo for intensity noise damped close to the relaxation oscillation frequency only and caused a very small amount of positive feedback at lower frequencies. (This is discussed in more detail in the Appendix.) In the frequency noise, the relaxation oscillation peak was reduced into the background noise.

The upper limit to frequency noise of this laser at the frequency of the relaxation oscillations is therefore about 1 Hz/√Hz, which reduces to an upper limit of about 0.4 Hz/√Hz when a servo to reduce relaxation oscillations in intensity noise is operating.

4. Conclusions

In our initial measurement we observed a residual relaxation oscillation in the frequency noise spectrum, probably caused by beam geometry fluctuations and intensity noise. In our later measurement, where greater care was taken with optical alignment, the residual peak at the relaxation oscillation frequency could probably be accounted for by intensity noise only. In both cases, the residual peak reduced when a servo system was operating which damped relaxation oscillations as observed in intensity noise.

For gravitational wave research we are particularly interested in using a miniature Nd:YAG ring laser to seed a high power Nd:YAG laser. These frequency noise measurements have shown that apparent relaxation oscillations in frequency noise are very small and can be reduced by damping the relaxation oscillation in intensity, and so are unlikely to cause problems in gravitational wave measurements at lower frequencies. Therefore, these miniature ring lasers can have very low noise at intermediate frequencies in addition to low noise at lower frequencies and look very attractive as master light sources for larger lasers in gravitational wave detectors.

5. References

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6. Acknowledgments

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7. Appendix

The servo system used to damp relaxation oscillations observed in intensity noise is shown in

Figure 4a. The relaxation oscillations are detected by monitoring some of the light on a photodiode. The signal from the photodiode is amplified and filtered using four differentiators to provide the large amount of phase lead needed to compensate for the 180° phase lag at the relaxation oscillation frequency, for a phase lag above about 11 kHz due to a low pass filter effect in the diode current driver, and for a few microseconds of time delay in the diode current driver. The amplified and filtered signal was fed back to the diode driver to control the diode laser pump current.

Some light was also split off to a separate photodiode which independently monitored the effects of the intensity servo.

In Figure 4b a schematic Nyquist plot for the open loop transfer function of the servo to reduce intensity noise is shown. At the frequency of the relaxation oscillation, the servo can reduce intensity noise by up to 20 dB and the relaxation oscillation is critically damped. At frequencies below about 150 kHz the servo system causes a slight increase in the noise background due to a small amount of positive feedback.

Figure Captions

Figure 1 Schematic diagram of the optical and electronic arrangement for the RF reflection locking circuit which measures frequency noise at the relaxation oscillation frequency.

Figure 2 First frequency noise measurement of the laser showing a peak at the relaxation oscillation frequency (250 kHz) and an intensity peak at 120 kHz resulting from a signal applied to the diode current driver. The relaxation oscillation peak corresponds to a frequency noise level of 7 Hz/√Hz. The centre of the diagram is 0 Hz, with a full screen frequency span of 750 kHz. The resolution bandwidth is 10 kHz. One side of the screen is a mirror image of the other side. The calibration of the vertical scale is 10 dB/division.

Figure 3 Noise spectrum on (a) one side and (b) other side of the dc position which minimised the 120 kHz intensity peak, showing an asymmetry in the relative sizes of the relaxation oscillation peak and the applied peak. The relaxation oscillation peak is at 350 kHz because a higher diode pumping current was used for these measurements. Screen centre is at 0 Hz, with a full screen frequency span of 1.5 MHz. The resolution bandwidth is 10 kHz. The calibration of the vertical scale is 10 dB/division.

Figure 4 Feedback circuit for damping relaxation oscillations in intensity noise.

a) Schematic diagram of the servo loop.

The high pass filtering consists of four differentiating circuits, operating over the ranges 13 kHz – 630 kHz, 230 kHz – 2.3 MHz, 66 kHz – 660kHz, 100 kHz – 3 MHz.

b) Schematic Nyquist plot for the open loop transfer function of the servo loop.

Figure 5 Frequency noise spectra. Diagram centres are at 0 Hz with a full screen span of 750 kHz. The applied intensity signal is at 180 kHz. The resolution bandwidth is 10 kHz. The calibration of the vertical scale is 10 dB/division.

a) Frequency noise spectrum showing the apparent relaxation oscillation peak at a level of ~ 1 Hz/√Hz without intensity servo operatin

b) Frequency noise spectrum when the relaxation oscillations in intensity noise are damped by the servo. The peak at the relaxation oscillation frequency is reduced into the background noise.

Figure 6 Intensity noise spectra. Diagram centres are at 0 Hz with a full screen span of 750 kHz. The applied intensity signal is at 180 kHz. The resolution bandwidth is 10 kHz. The calibration of the vertical scale is 10 dB/division.

a) Intensity noise of the free-running laser;

b) Intensity noise of the laser when the intensity servo is operating. These measurements correspond to the frequency noise measurements shown in Figure 5.

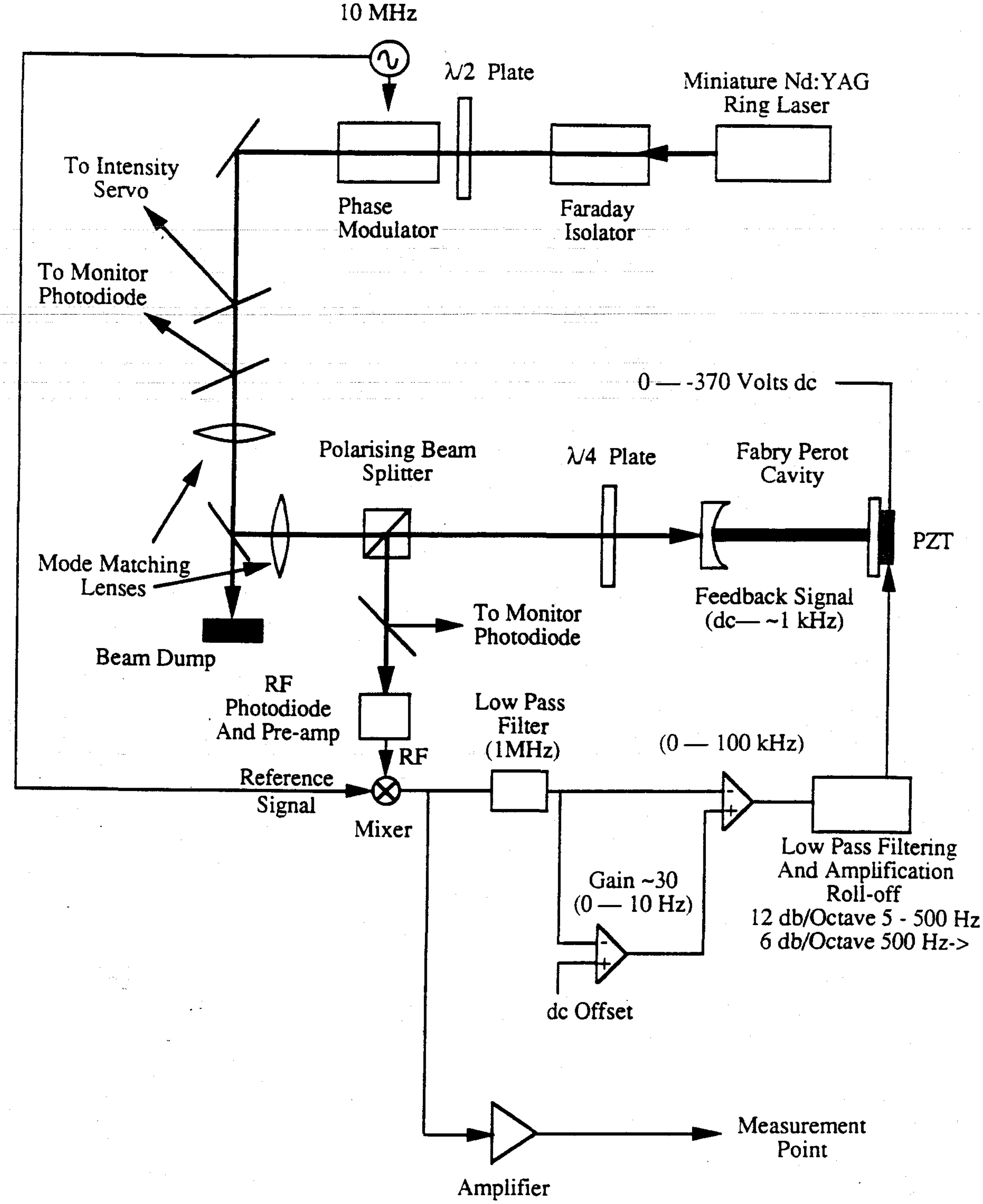

FIG 1

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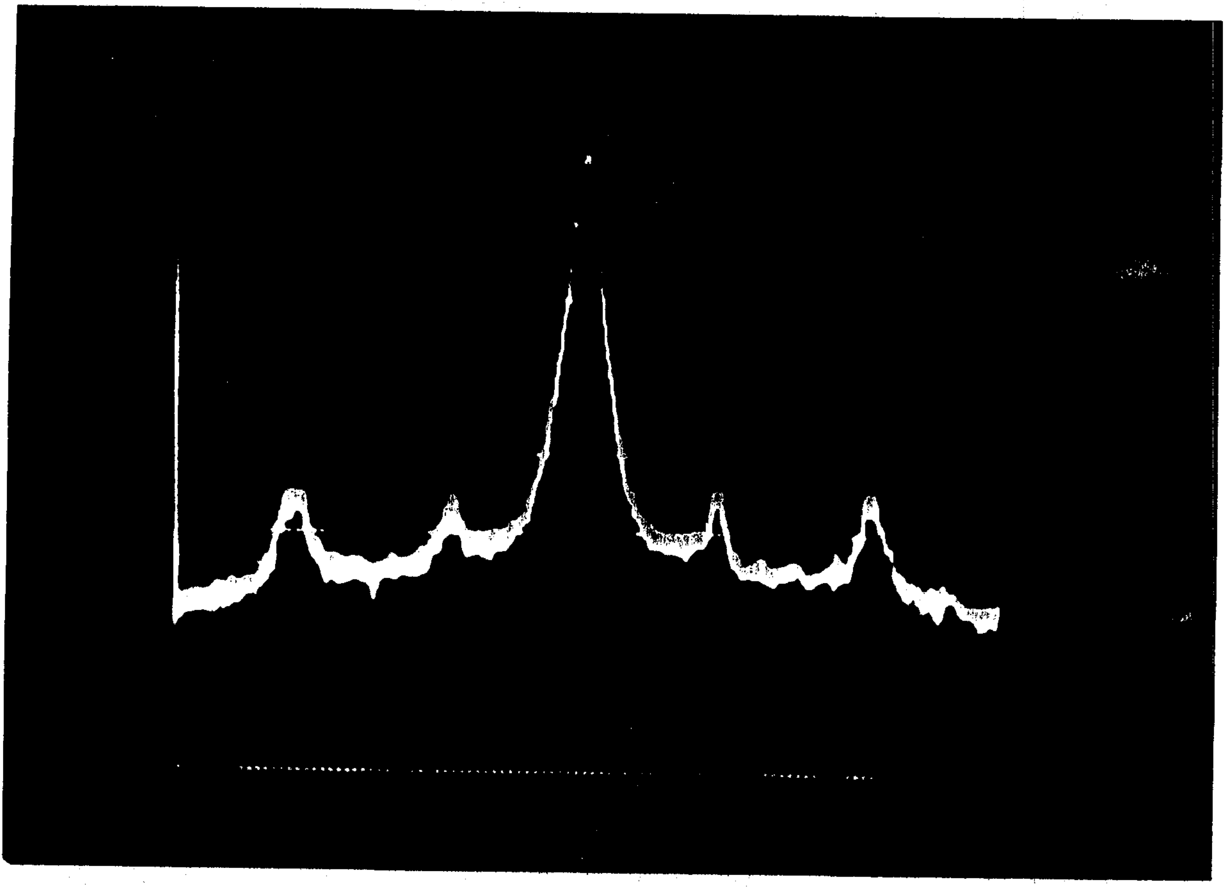

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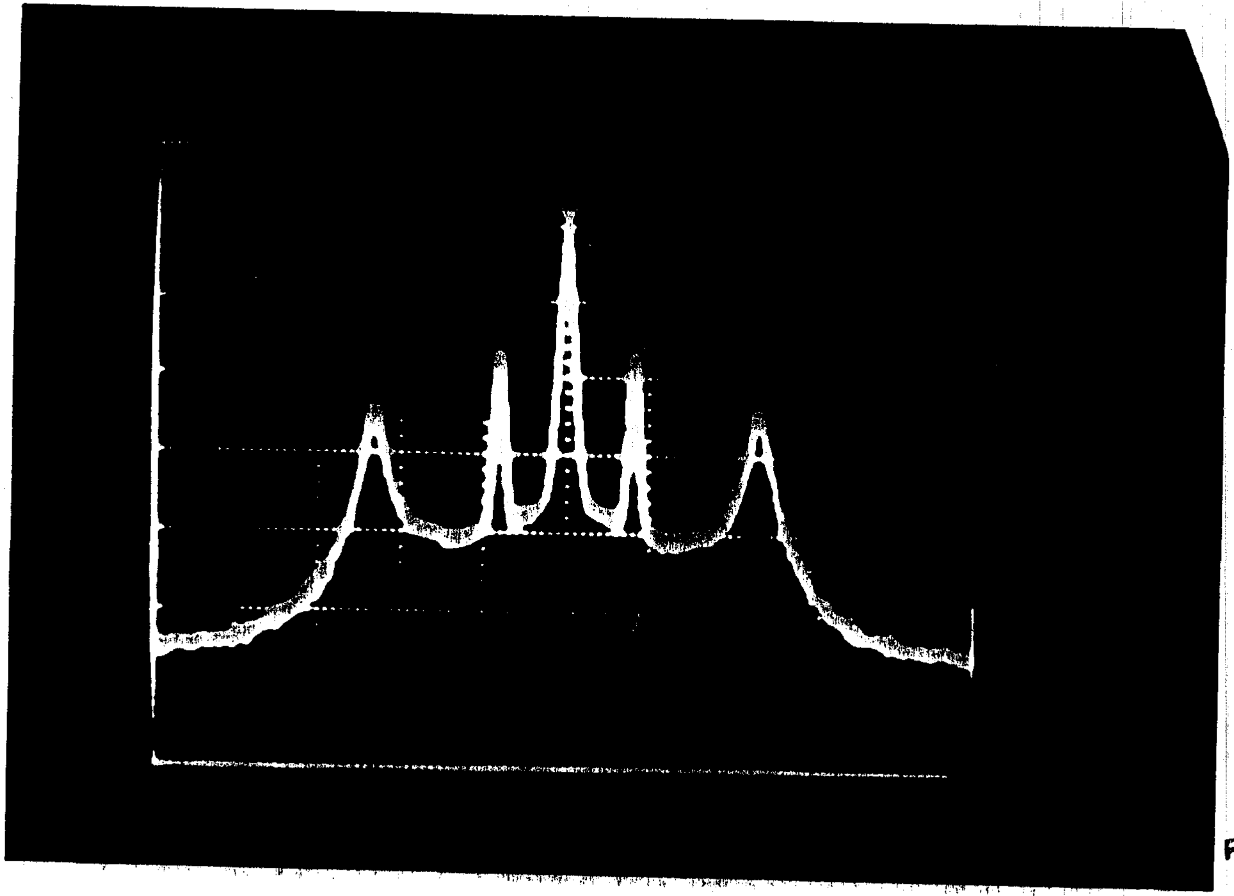

FIG 3(a)

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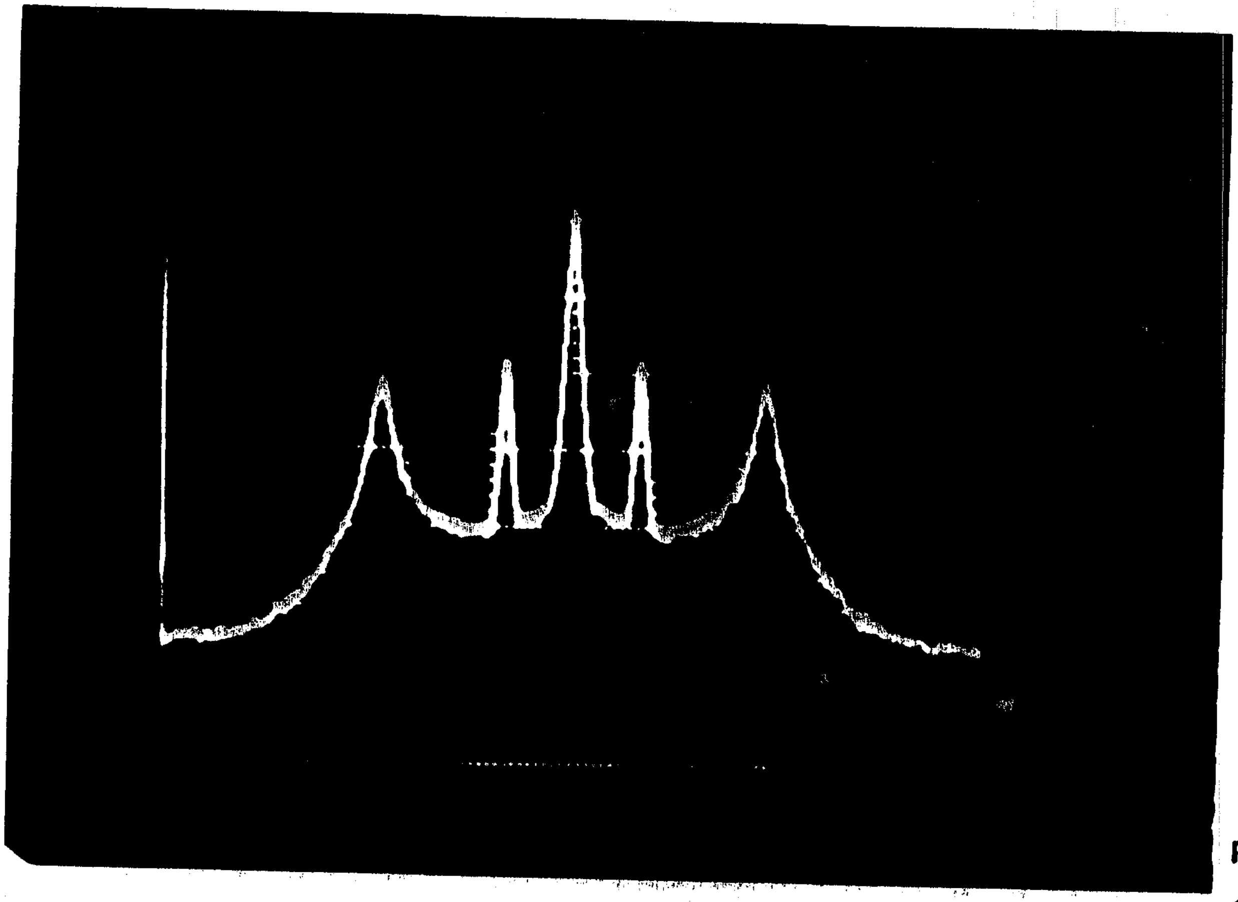

FIG 3(b)

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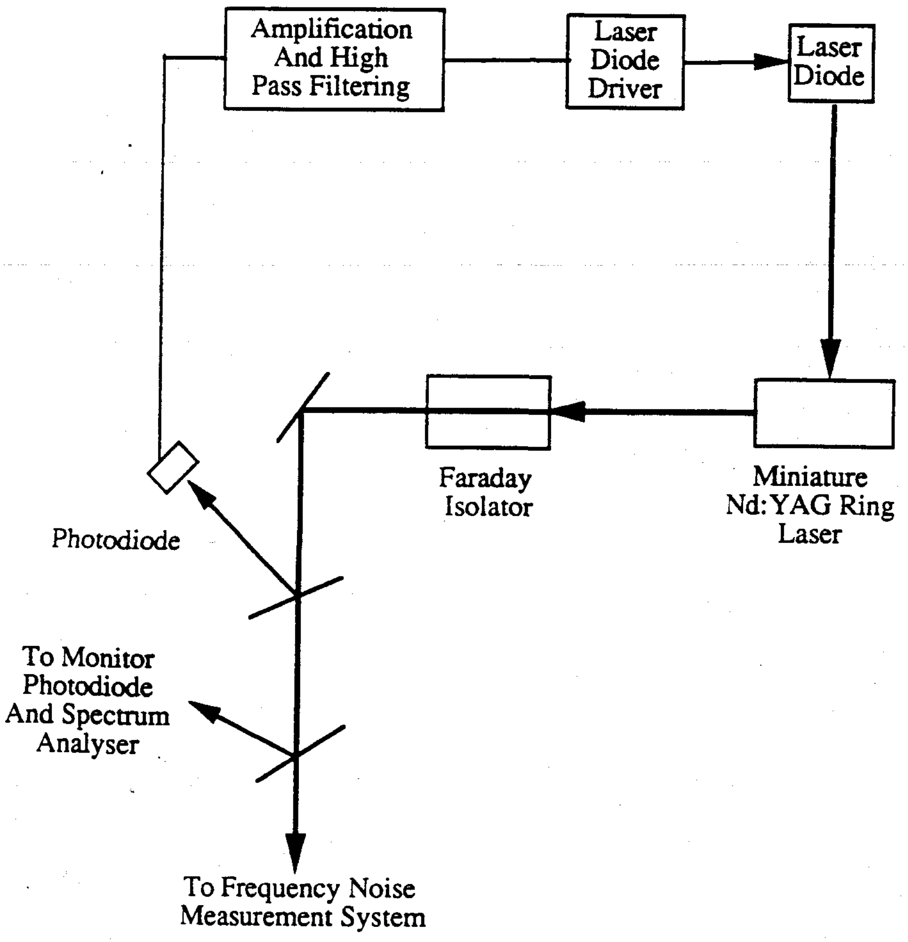

FIG 4(a)
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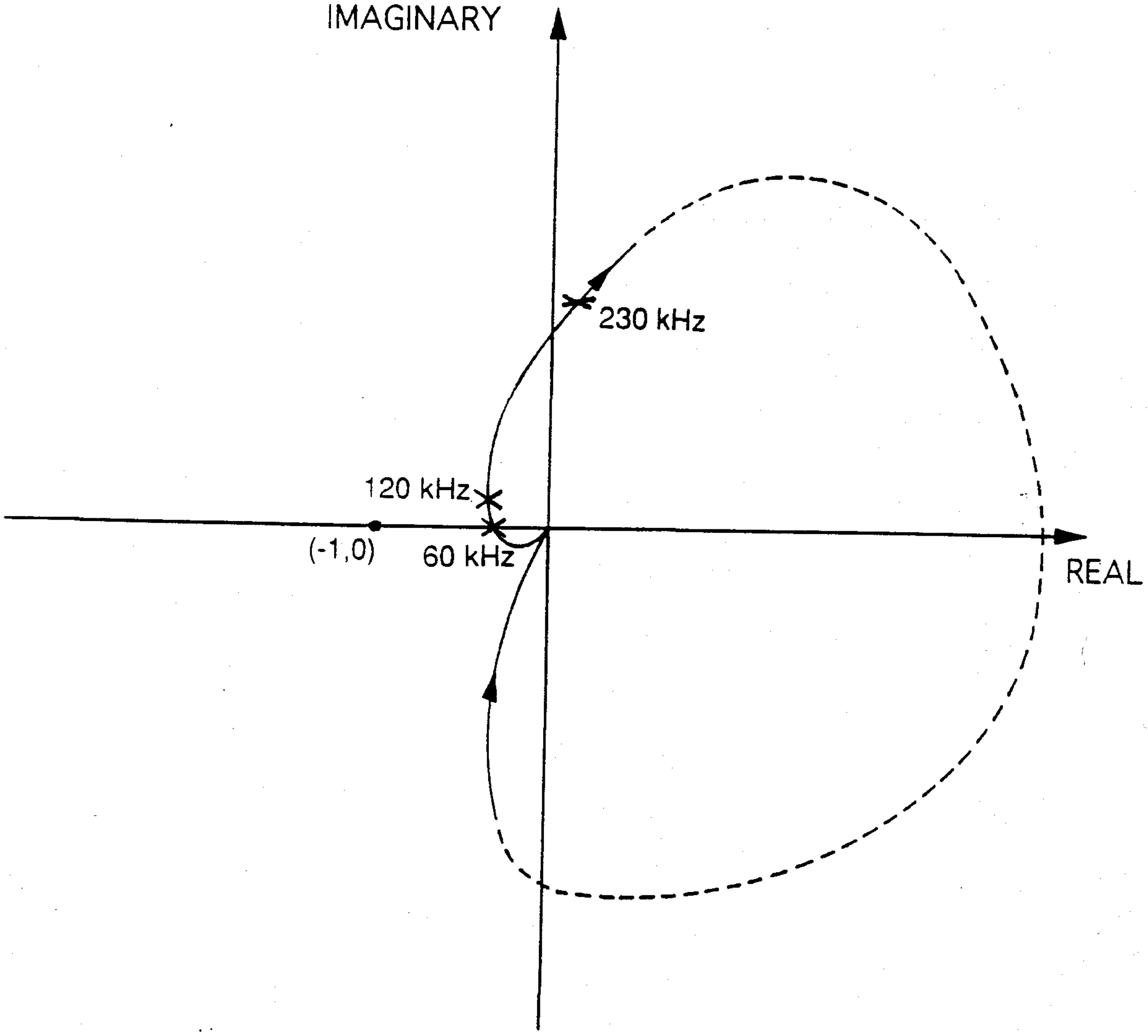

FIG 4(
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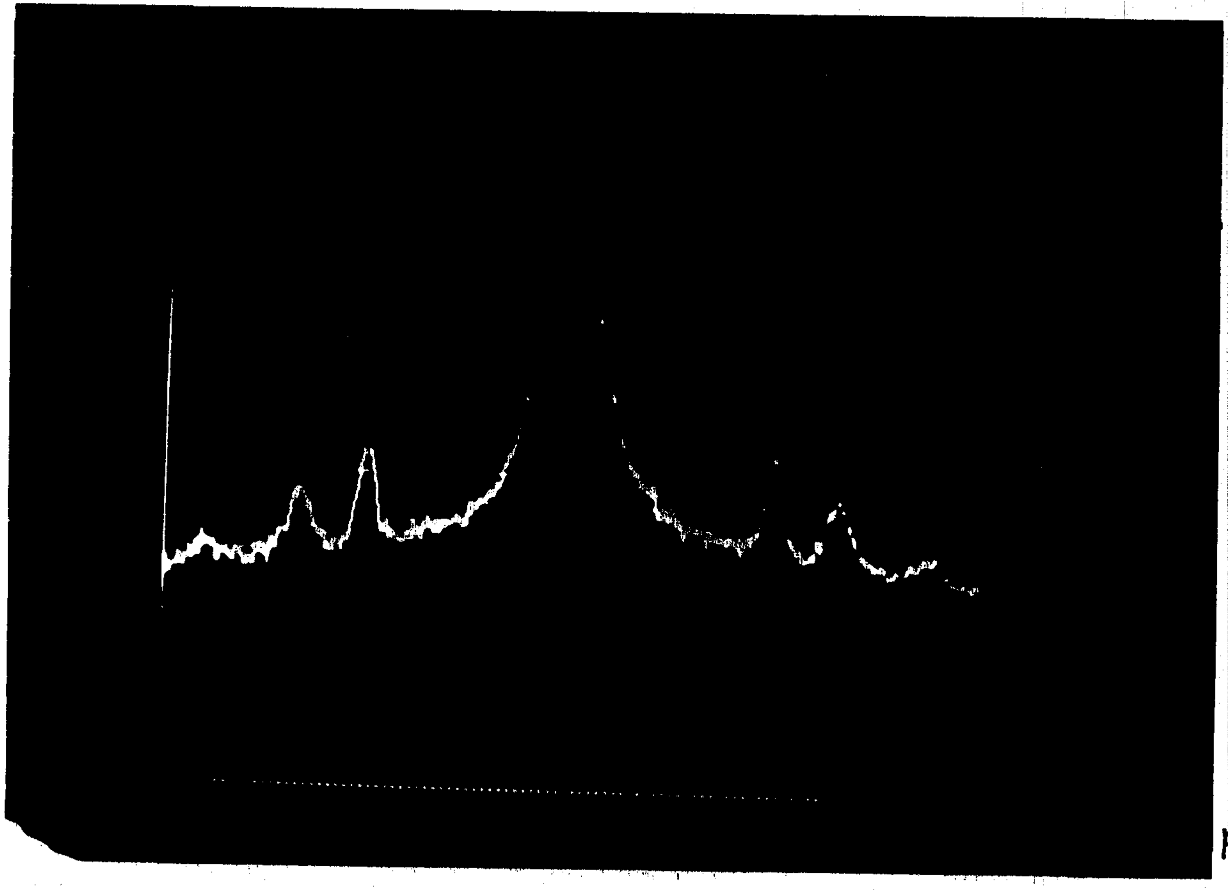

Fig 5(a)

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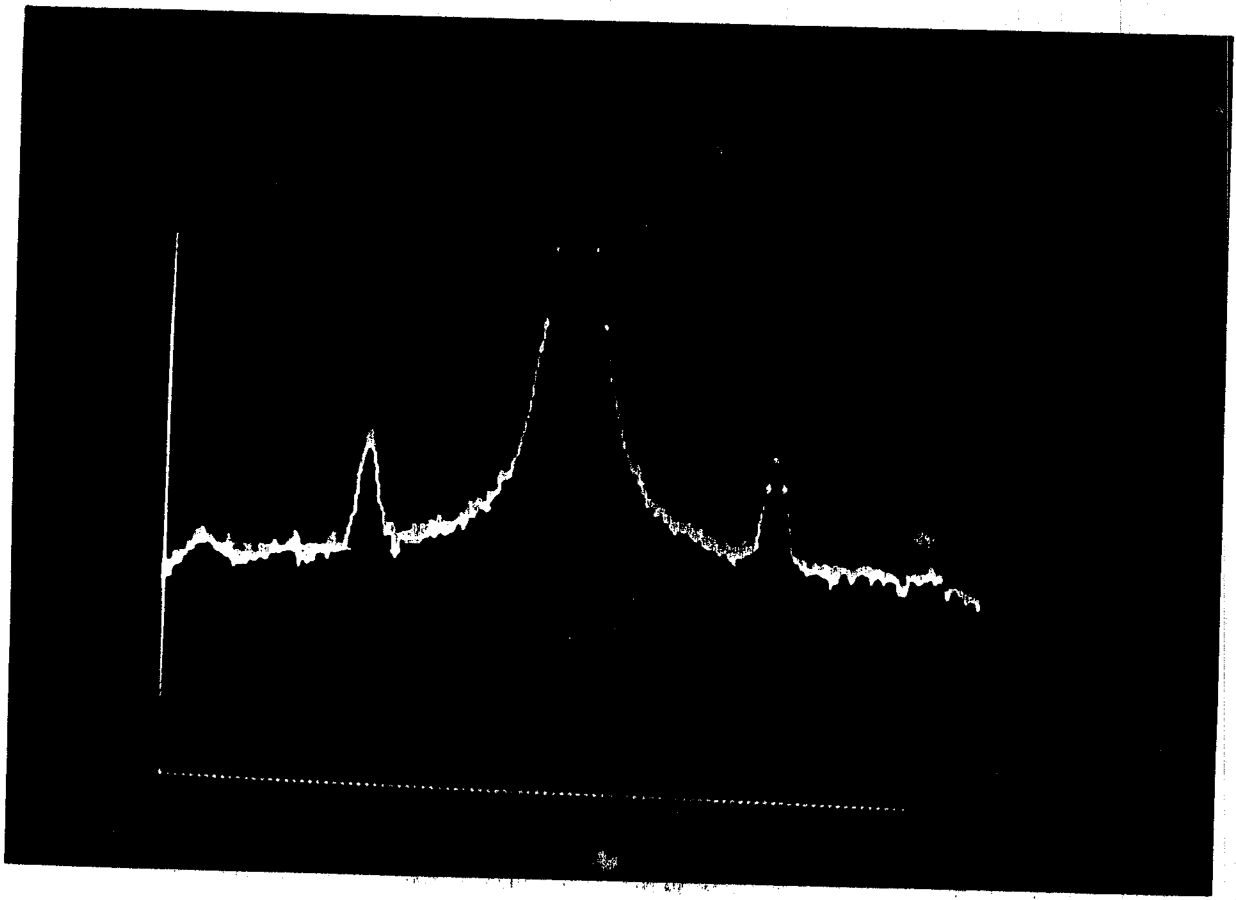

Fig 5(b)
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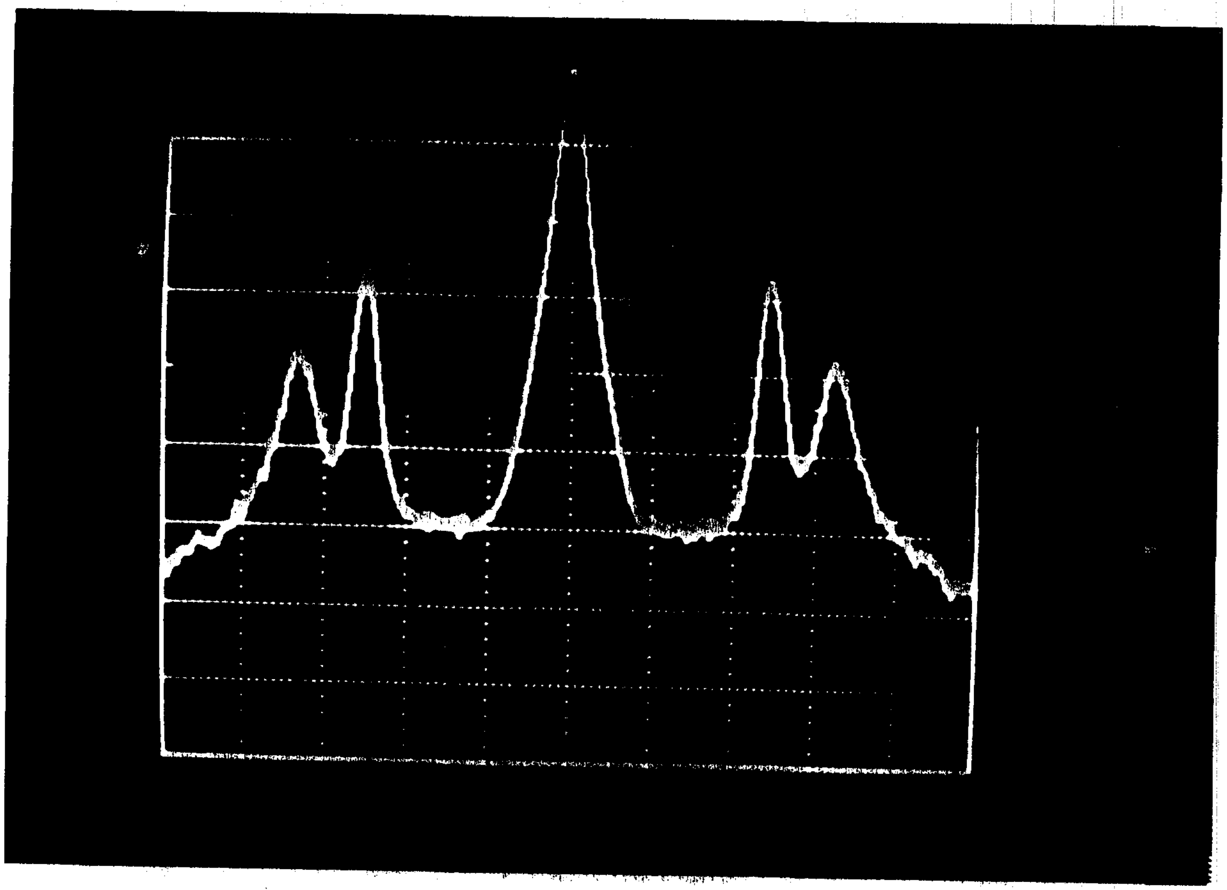

FIG 6(a)

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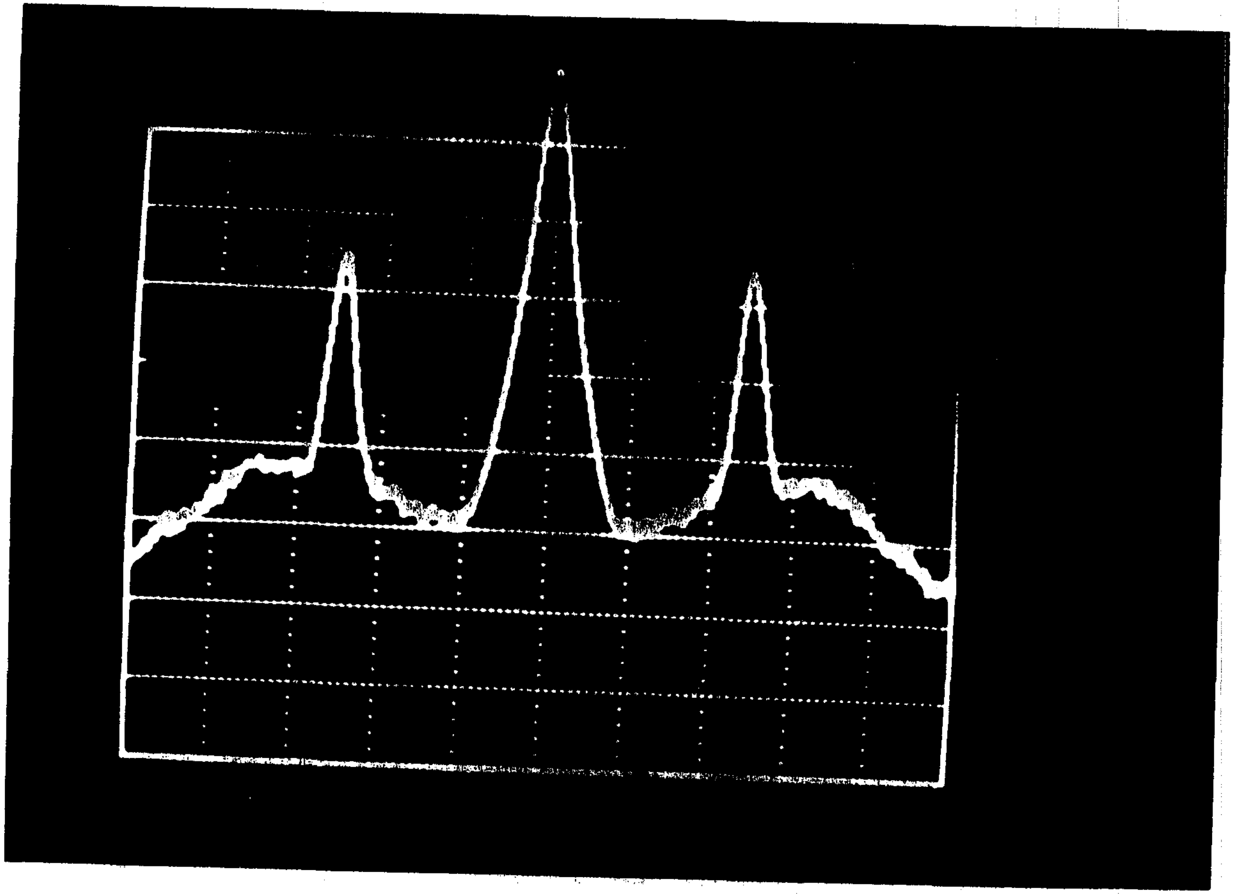

FIG 6(b)
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