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A STARK TUNED, FAR-INFRARED LASER
FOR HIGH FREQUENCY PLASMA DIAGNOSTICS

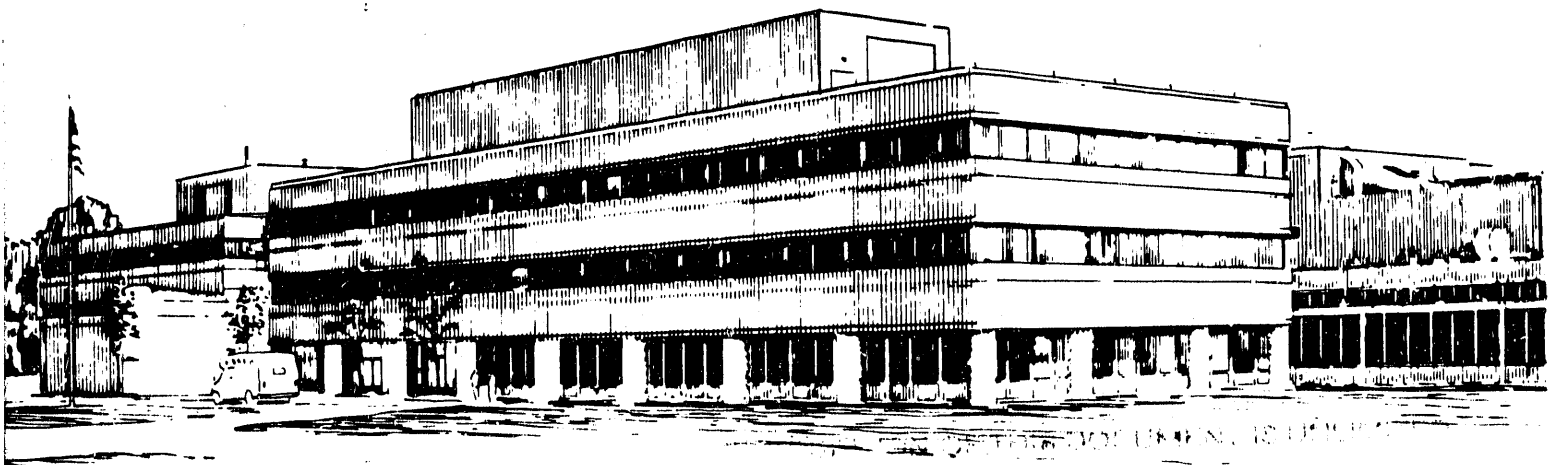
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A STARK-TUNED, FAR-INFRARED LASER FOR HIGH FREQUENCY PLASMA
DIAGNOSTICS⁺

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ABSTRACT

A Stark-tuned optically pumped far-infrared methanol laser operating at 119 micrometers has been built. The laser is designed to operate at high power while exhibiting a well-separated Stark doublet. At a pump power of 65 Watts and electric field of 1 kV/cm the laser has delivered over 100 mW c.w. while exhibiting a frequency splitting of 34 MHz. These parameters indicate that this laser would be suitable for use in the present generation of modulated interferometers on large thermonuclear plasma devices. The achieved modulation frequency is more than an order of magnitude higher than could be achieved using standard techniques.

Key words: Stark-tuned FIR laser, plasma diagnostics

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INTRODUCTION

At present, on large thermonuclear plasma devices, modulated far-infrared (FIR) laser interferometers are the most common diagnostic employed for measuring the electron density [1,2]. The modulation frequency is typically introduced into these interferometers either mechanically by a rotating grating or optically by mistuning the output frequencies of two independent FIR lasers and then mixing those two outputs together to obtain a beat signal. The maximum modulation frequency obtainable by the former method is typically limited to between 10 kHz and 100 kHz by mechanical considerations. The maximum beat frequency obtainable by the optical method is typically 1-3 MHz and is limited by the narrow gain bandwidth available in these types of lasers (FWHM \approx 5-8 MHz, at low pump power).

In practice, a nagging problem associated with these low (≤ 1 MHz) modulation frequencies is that they result in the loss of fringe count during rapid changes in the plasma density. Such rapid changes typically occur on large plasma devices during the injection of solid pellets for fueling, during extreme cases of MHD activity and during major disruptions. In order to harden an interferometer against such problems it would be desirable to increase the modulation frequency significantly. This is because, at its most fundamental level, a modulated interferometric measurement is made by comparing the phase between two sinusoidal beat signals - the reference and scene signals:

$$V_{\text{ref}}(t) \propto \cos(\Delta\omega t) \quad (1)$$

and

$$V_{\text{scene}}(t) \propto \cos(\Delta\omega t + \zeta(t)). \quad (2)$$

Where $\Delta\omega$ is the modulation frequency and $\zeta(t)$ is the phase difference between the two signals which is impressed on $V_{\text{scene}}(t)$ by the passage through the plasma column of one of the laser beams generating the beat signal. That is:

$$\zeta(t) \propto \int n(r,t) dl, \quad (3)$$

where the integral of the plasma electron density $n(r,t)$ is taken along the path of the laser beam. When the rate of change of the line integrated density becomes so large as to be comparable to $\Delta\omega$,

it is no longer possible to measure the phase difference between the two signals. Hence, to ensure that a measurement can always be made, it is necessary that:

$$|\partial\zeta(t)/\partial t| \ll \Delta\omega. \quad (4)$$

In order to ensure that (4) is fulfilled it is desirable to make $\Delta\omega$ as large as possible and certainly larger than 1 MHz.

In addition to the considerations given above, as a practical matter, the power levels needed to run a multi-channel interferometer on a large plasma device are typically several tens of milliwatts to several hundreds of milliwatts [2]. Therefore, any technique employed to enhance the modulation frequency must be viable at the highest achievable FIR power levels.

In this regard, Biouducci has demonstrated that, at low pump power levels, the gain curve of the 119 μm line of CH_3OH breaks into two equivalent gain curves when the gain medium is immersed in a uniform electric field [3]. Further, the frequency difference between these two gain curves is simply proportional to the applied electric field. The 119 μm line happens to be the most powerful c.w. line available in the FIR and is therefore widely used by the plasma physics community in the present generation of modulated interferometers [1,2]. In the work to be described, the Stark effect has been exploited in a CH_3OH laser designed to be powerful enough to be used on a tokamak or other large plasma device while simultaneously capable of producing a very high modulation frequency.

2. DESIGN AND CONSTRUCTION

The design of the FIR resonator tube is shown in Fig 1. The tube consists of a rectangular pyrex tube with 2 mm thick walls and with inside dimensions of 22 mm x 9.5 mm. These particular dimensions have been demonstrated to be nearly optimal in order to avoid pump laser loss and resonances [3]. In order to apply a uniform electric field to the gain medium, the two large inside faces of the rectangular tube were coated with aluminum by a process described below. The rectangular tube is surrounded by a cylindrical pyrex water jacket. This design allows the entire structure to be water-cooled without fear of electrical breakdown or the need for an oil coolant. The enhancement of the FIR output power due to this kind of temperature control of the resonator walls has been described elsewhere [4].

The input coupler consists of a flat gold-coated copper mirror with a centered 4 mm input coupling hole. A hybrid metal-dielectric mirror with a 6 mm Si aperture is employed as the output

coupler [5]. Water-cooling of the input and output couplers as well as of the resonator walls provides active thermal stabilization of the cavity. Passive thermal stabilization of the cavity structure is accomplished in the standard way with the use of four Super-Invar rods. Two versions of this resonator were constructed. The original version had a length of 1 meter while the later version had a length of 2 meters.

The grating-tuned CO₂ pump laser delivered 70 Watts on the 9P(36) line. This laser has also been described elsewhere [4]. The pump power is focussed into the FIR resonator by a ZnSe lens with a 75 cm focal length. The orientations of the pump and FIR polarizations are also indicated in Fig 1.

The inside of the rectangular tube was coated by evaporating a conducting film of aluminum onto the two large faces. The evaporation process involved pulling a movable tungsten filament along the length of the rectangular tube. The filament was preloaded with high purity aluminum. A shield which moved with the resistively heated filament prevented the two small faces of the tube from also being coated. The 1 μ m thickness of the film is much larger than the skin depth of aluminum at the laser operating frequency (≈ 54 nm). Hence, this film acted as a highly conducting waveguide wall. The DC electrical connections to the metallic film electrodes were made by simple mechanical contact.

3. PERFORMANCE

Figure 2 shows the output power of the 2 meter FIR resonator as a function of cavity length. The pyroelectric detector used in this scan was located about 2 meters from the output coupler. The absolute output power was determined with a calorimeter. With the use of a sheet of high sensitivity liquid crystal, the cavity modes shown in Fig 2 have been seen to couple efficiently to free space TEM₀₀ modes. The laser output, when viewed with the liquid crystal, was clearly circularly symmetric. The extremely clean cavity mode structure shown in Fig. 2 is due to the low effective Fresnel number (≈ 0.2) of the rectangular cavity. A somewhat more crowded mode structure was observed with the 1 meter cavity owing to a larger Fresnel number.

With the application of an intracavity electric field the gain curve is seen in Fig 3 to break into two distinct gain curves with the doublet separation linearly dependent on the electric field strength. However, it should be noted that the doublet separation (≈ 35 MHz) achieved at ≈ 1 kV/cm is somewhat larger than expected based on previous work [3]. This enhanced splitting is not understood, but may be due to the increased pump power employed in this work as compared to previous studies of the Stark splitting of this line.

Because, for the geometry of our Stark laser, the breakdown voltage in methanol reaches a minimum at a lower pressure than the optimum pressure for submillimeter lasing efficiency, it is necessary to trade-off FIR power for the ability to apply higher fields without breakdown [3]. That is to say, one wants to operate at a pressure which will ensure the most FIR power at a given doublet separation. For the 2 meter laser described in this work, that operating pressure was found to be 170 mT resulting in a doublet separation of ≈ 35 MHz. The FIR power achieved at this pressure is 110 mW. At the optimum pressure (400 mT) the maximum power delivered by the laser with no electric field is 215 mW. This trade of power for frequency does not seem too serious a compromise in light of the fact that very reasonable c.w. output power (110 mW) is achieved at a doublet separation at least an order of magnitude higher than can be achieved by other methods.

Shown in Fig 4 is a beat spectrum as observed with a Schottky diode mixer. The output from the 1 meter long Stark laser was mixed with the output from a standard, unshifted CH_3OH laser. At an electric field strength of 700 V/cm a clear shift of ≈ 14 MHz is observed. The frequency of this beat note was seen to vary roughly linearly as the field strength was shifted over the range of 600-1000 V/cm. This figure clearly demonstrates that the mode spectrum of the Stark resonator is sufficiently free of transverse modes to allow single frequency operation for the purposes of interferometry. If a second Stark-shifted laser had been available, at least twice as high a beat frequency would have been generated.

At these high pump power levels (> 50 Watts) no clear Stark doublet was observed below ≈ 500 -600 V/cm. This is assumed to be due to the combined effects of power and pressure broadening on the FIR gain curve. The increased bandwidth caused by these effects is also evident in the unshifted cavity scan of Fig 2.

It should also be pointed out that, at the highest pump power, a FIR power enhancement of 10-20% is seen at low field strength (≈ 250 V/cm) due to the non-linear Hanle effect. This effect has been well documented elsewhere [3]. However, at the operating point of Fig 3, no enhancement is expected or observed because the applied electric field is larger than the optimum field for power enhancement.

4. DISCUSSION

It has thus been demonstrated that this method can lead to a high modulation frequency while simultaneously delivering high output power. This ability to generate higher modulation frequencies will allow future plasma interferometers to be hardened against fringe loss due to rapid density changes. In addition, increased modulation frequencies will allow much higher data rates to

be achieved for the study of transient plasma effects as well as very high frequency plasma modes. As shown in Fig 5 (a) there are other advantages to this technique. This figure shows the standard method of achieving a 1 MHz modulation frequency employed in the present generation of modulated interferometers. With the advent of this high power, Stark-tuned laser it becomes possible to adopt the method shown in Fig 5 (b). In this scheme, the two lasers are tuned to the top of Stark-shifted gain curves rather than on the sides of unshifted gain curves. Thus the output power is not "wasted". In addition, the scheme summarized in Fig 5 (b) should be fundamentally more stable over long periods of time because each laser is operating at the peak of a gain curve rather than on the side. Further, small adjustments can be accomplished with an electric field/voltage change rather than by mechanically changing the cavity length.

Many of the present generation of modulated interferometers employ Schottky diodes as detectors [6]. An additional benefit of using higher modulation frequencies can be realized because at low frequencies ($<1\text{MHz}$), these diode detectors are limited by $1/f$ noise. By increasing the modulation frequency beyond the 1 MHz range, for a fixed power level, the signal to noise ratio should increase as the frequency is increased.

REFERENCES

1. S. M. Wolfe, K. J. Button, J. Waldman and D. R. Cohn, "Modulated Submillimeter Laser Interferometer System for Plasma Density Measurements," *Appl. Opt.* **15**, 2645-2648 (1976).
2. D. K. Mansfield, H. K. Park, L. C. Johnson, H. M. Anderson, R. Chouinard, V. S. Foote, C. H. Ma and B. J. Clifton, " Multichannel Far-Infrared Laser Interferometer for Electron Density Measurements on the Tokamak Fusion Test Reactor," *Appl. Opt.* **26**, 4469-4474 (1987).
3. G. Bionducci, M. Inguscio, A. Moretti and F. Strumia, "Design of Molecular FIR Lasers Frequency Tunable by Stark Effect: Electric breakdown of CH₃OH, CH₃F, CH₃I and CH₃CN," *Infrared Phys.* **9**, 297-308 (1979).
4. D. K. Mansfield, E. Horlbeck, C. L. Bennett and R. Chouinard, "Enhanced, High Power Operation of the 119 um Line of Optically Pumped CH₃OH, " *Int. J. Infrared and Millimeter Waves* **6**, 867-876 (1985).
5. D. T. Hodges, F. B. Foote and R. D. Reel, " Efficient high-power operation of the CW Far-Infrared Waveguide Laser," *Appl. Phys. Lett.* **29**, 662-664 (1976).
6. H. R. Fetterman, P. E. Tannenwald, B. J. Clifton, C. D. Parker, W. D. Fitzgerald and N. R. Erikson, " Far-IR Heterodyne Radiometric Measurements with Quasioptical Schottky Diode Mixers," *Appl. Phys. Lett.* **33**, 151-154 (1978).

FIGURE CAPTIONS

- Fig 1. A cross section of the FIR resonator tube used in this work. Also shown is the orientation of the FIR and pump polarizations.
- Fig 2. A cavity scan from the 2 meter Stark laser with no applied field. The cavity modes shown coupled efficiently into TEM₀₀ free space modes.
- Fig 3. A cavity scan from the 2 meter Stark laser with the CH₃OH pressure lowered to allow the application of a ≈ 1 kV/cm electric field without breakdown. This operating point was chosen as a trade-off between power and doublet splitting. A doublet splitting of ≈ 35 MHz is clearly seen at a power level above 100 mW.
- Fig 4. A beat spectrum (2 MHz/div) from the unshifted output from a standard FIR laser mixed with the 1 meter Stark-shifted laser output. A modulation frequency of ≈ 14 MHz is clearly seen. The component at ≈ 1 MHz is from an unwanted transverse mode in the unshifted laser. A Schottky diode was used as the mixer. The laser configuration associated with the measurement is shown in the insert.
- Fig 5.(a) The optical method of generating the modulation frequency in the present generation of FIR interferometers. Two lasers (A & B) are tuned on opposite sides of a narrow gain curve. This technique is limited by the gain bandwidth to frequencies around 1MHz. (b) In this work, the gain curve is Stark-split and the lasers are tuned to the two available peaks. The modulation frequency and long-term stability are thus greatly increased.

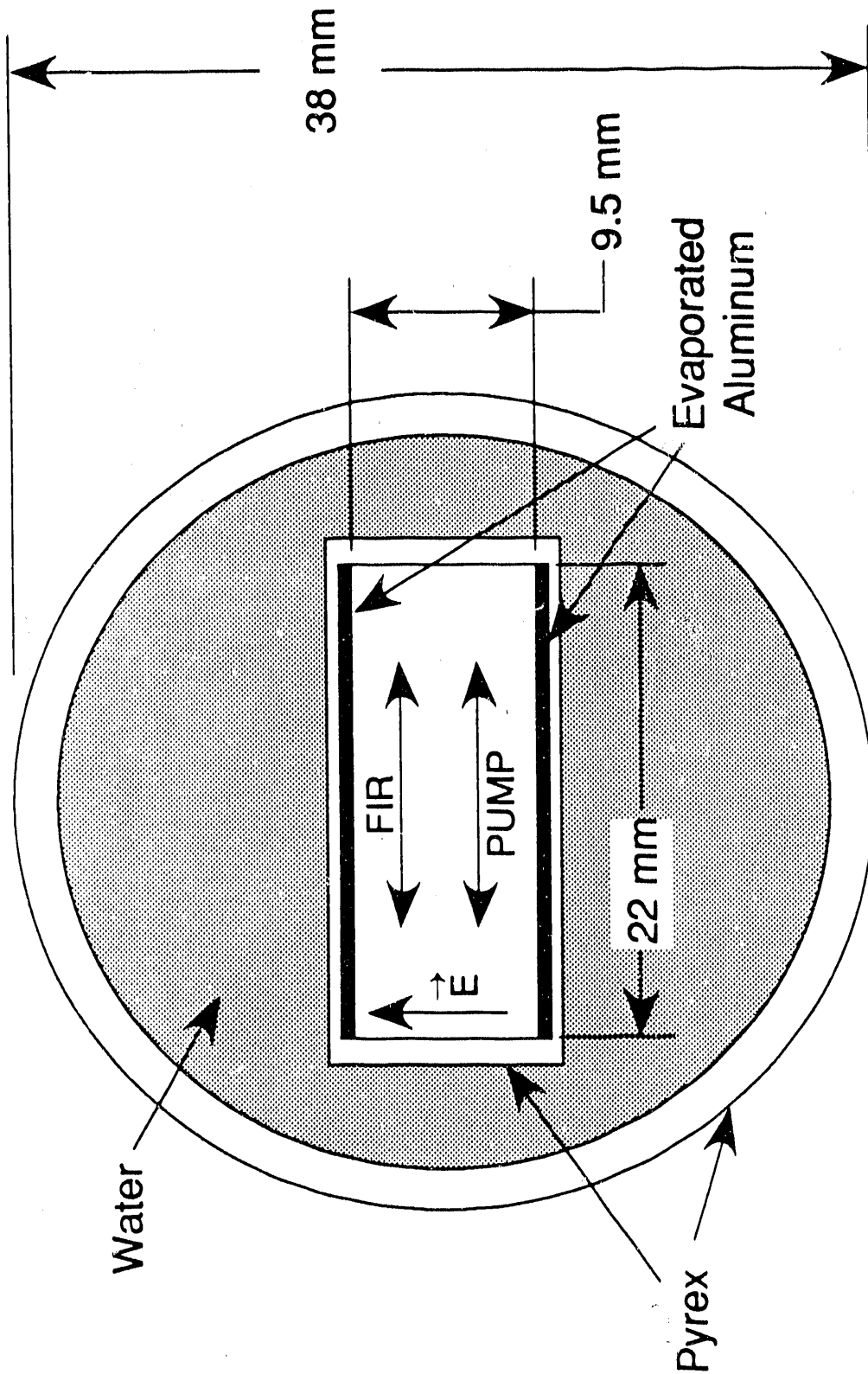


Fig. 1

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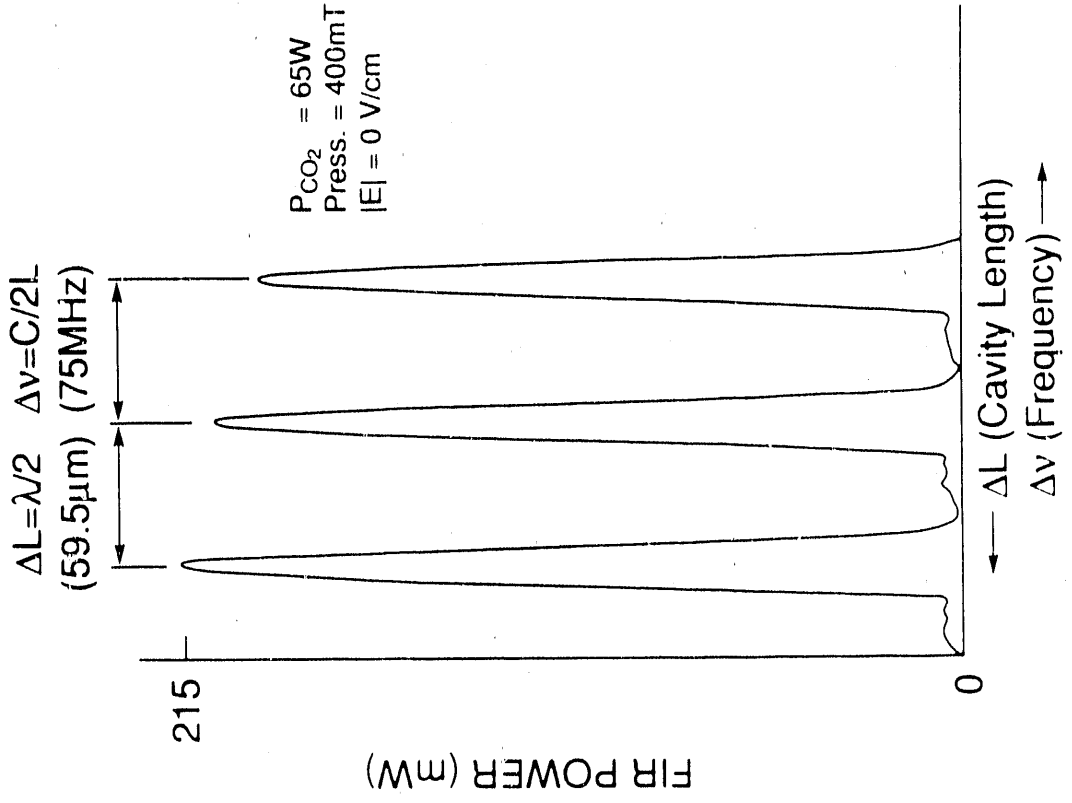


Fig. 2

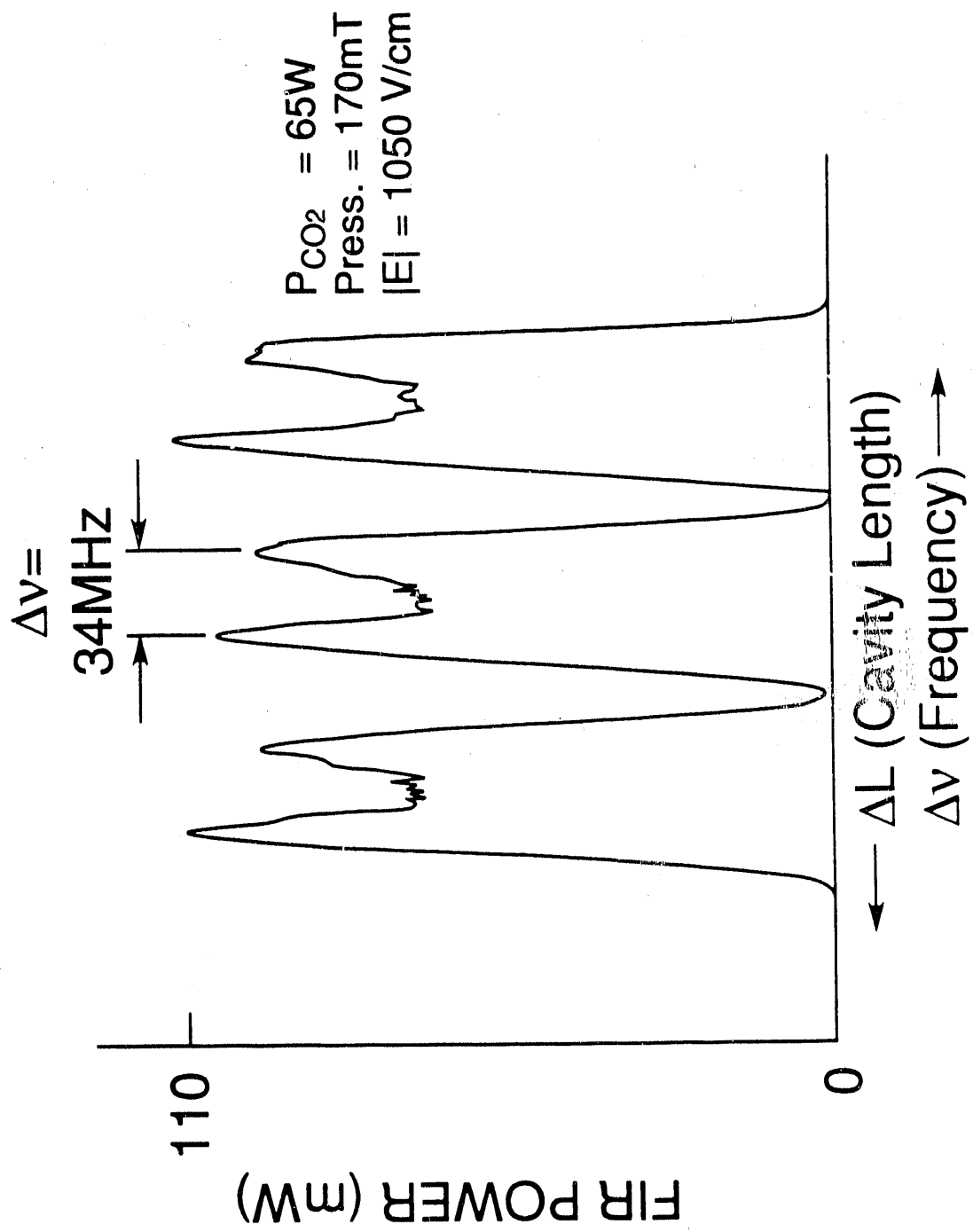
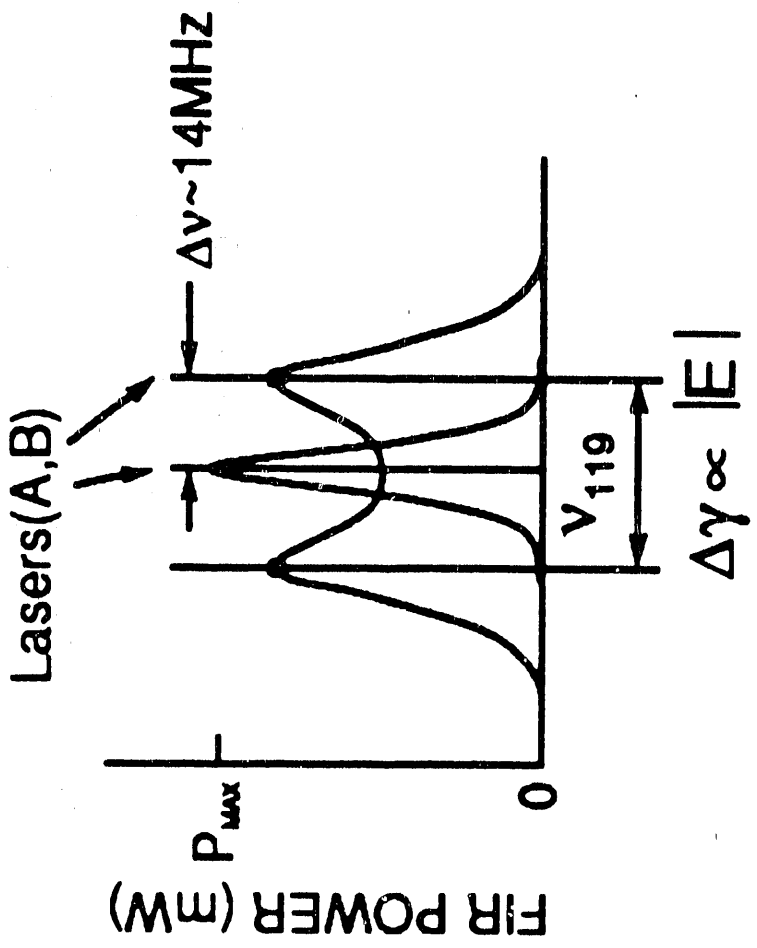
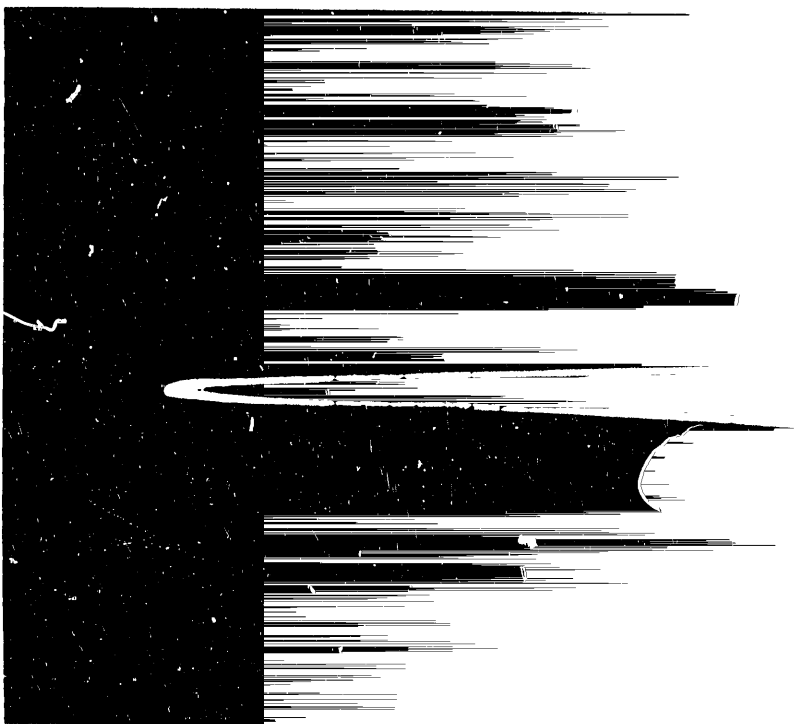


Fig. 3



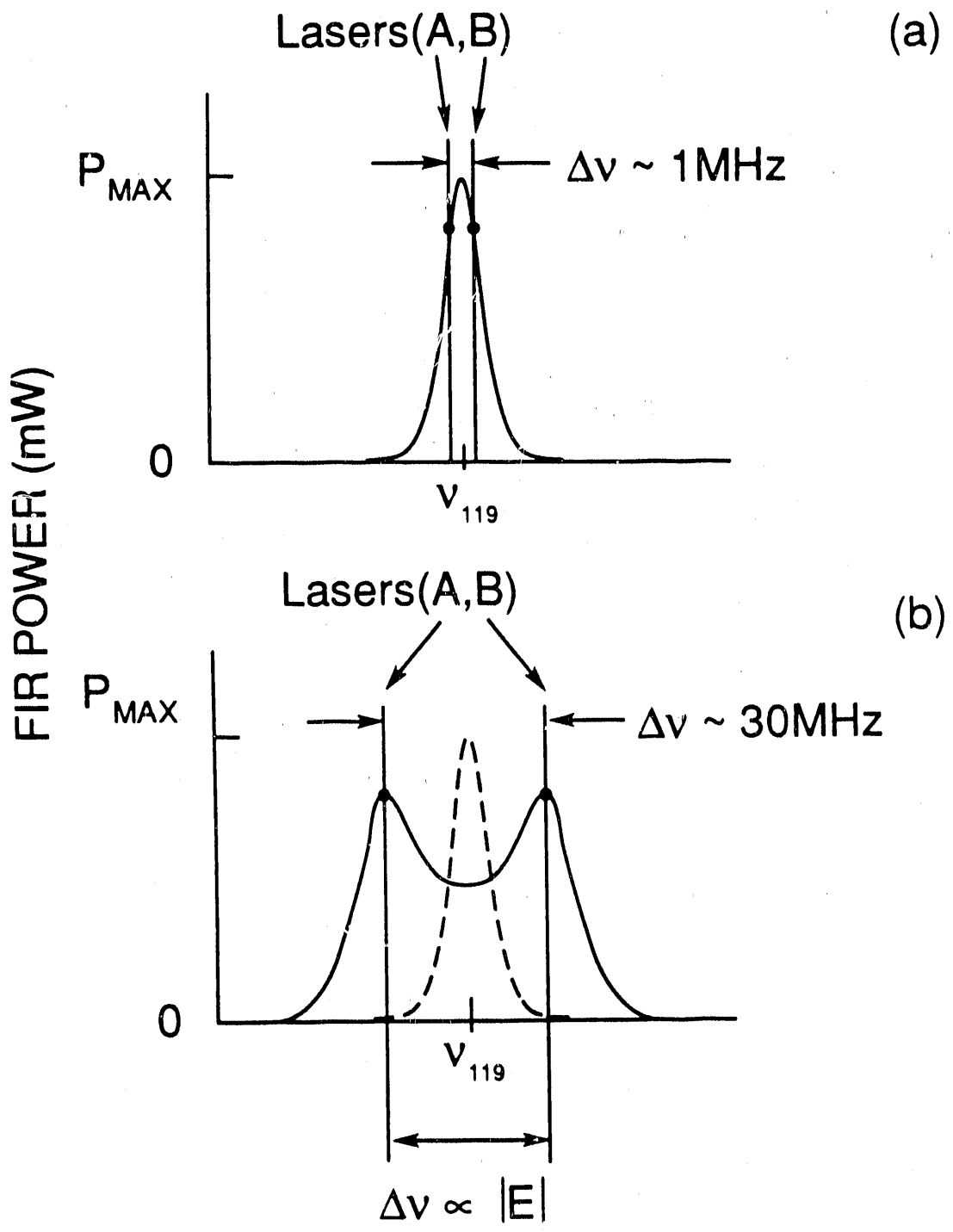


Fig. 5

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