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Beat Frequency Stabilization between two HCN Lasers by Phase Locked Loop

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The frequency stabilization circuit using a phase locked loop (PLL) was developed to stabilize a beat frequency of HCN laser interferometer in the JFT-2M tokamak. The application of this frequency stabilization circuit is to observe waves and density fluctuations in plasmas by laser scattering measurement. The frequency resolution of PLL is less than 10 kHz. The lock range obtained experimentally is about 1 MHz and its value is high enough to stabilize the beat frequency between two HCN lasers. The present PLL circuit can be applied to the scattering experiment in JFT-2M.

Keywords; Phase Locked Loop, HCN Laser Interferometer, Frequency Stabilization, Laser Scattering, JFT-2M

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位相ロックループによる２台のHCNレーザーのビート周波数の安定化

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位相ロックループ（PLL）を用いた周波数安定化回路が，ＪＦＴ－２Ｍに設置されているＨＣＮレーザー干渉計のビート周波数を安定化するために開発された。周波数安定化の目的は，レーザー散乱測定によりプラズマ中の密度揺動や波動を観測するための散乱測定装置に応用することである。ＰＬＬ回路の周波数分解能は10 KHz 以下である。実験により得られた周波数ロック幅は，約１MHz であり，２台のHCNレーザーのビート周波数を十分安定化できる値である。今回開発されたPLL回路は，ＪＦＴ－２Ｍにおける散乱測定に用いることが可能であることが判明した。

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Contents

目　　次

1. Introduction

Collective scattering of electromagnetic waves is an effective method to determine the structures of density fluctuations or waves in plasmas[1]. Homodyne and heterodyne detection systems have been employed for receivers in scattering experiment[2]. In usual homodyne systems, One oscillator is used both for incident and local signals. A high frequency resolution is easily attained without a special frequency stabilization. However, it is impossible to identify the direction of the wave propagation determined by the relations[1],

$$\overline{K}_s = \overline{K}_i \pm \overline{k}$$

$$\omega_s = \omega_i \pm \omega, \qquad (1)$$

where $\overline{K}_s$, $\overline{K}_i$ and $\overline{k}$, ω_s, ω_i and ω are the wavenumber vectors and frequencies of the scattered and incident signals and the density fluctuation in plasmas, respectively. And when detecting externally excited waves, the signal to noise ratio is lowered by the direct coupling of the driver signal since the frequency of the mixed down signals is same as that of the driver signal.

In the heterodyne receiver system, two oscillators are required for the incident and local signals, and therefore a frequency stabilization is essential to obtain a high frequency resolution. The scattered signals can be resolved into the up-shifted and down-shifted frequencies which depend on the wave propagation in plasmas. The receiver is hardly affected by the direct coupling from the wave driver since the frequency of the observed signals is different from that of the wave driver.

In general, there have been two methods to stabilize the frequency fluctuation in heterodyne receiver[3]. One method is to feed back the error voltage which is converted from the beat frequency of two oscillators by a frequency-voltage converter(FVC) to a voltage controlled local oscillator. In the other method, the error voltage is obtained through a phase detection between the beat signal and the output from the second local oscillator with a good frequency stability. This feedback loop is called "Phase Locked Loop(PLL)". Since it becomes difficult to convert frequency to voltage by FVC at a high frequency increases, and a high frequency resolution can be obtained by means of phase detection system, PLL is employed to stabilize the beat frequency in the present HCN laser system of JFT-2M tokamak[4]. In this paper, we report the performance characteristics of PLL circuit and its application to the scattering measurement in JFT-2M.

2. Frequency Stabilization Circuit

2.1 Phase Locked Loop

The phase locked loop(PLL) is a closed feedback circuit on frequency and phase. The application of PLL is PLL/FM demodulator, FM stereo multiplexer circuit and so on[3]. Recently, integrated circuits of PLL are available up to 1 GHz. The basic circuit of PLL is shown in Fig.1. It consists of a phase detector(ϕ DET), a low pass filter(LPF) and a voltage controlled oscillator(VCO). The phase detector produces an error observed signals is different from that of the wave driver.

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2.2 Frequency Stabilization by PLL

The block diagram of PLL circuit is shown in Fig. 2. The beat frequency between the probe and reference HCN lasers is introduced to PLL. It is mixed with the output from VCO in a mixer-1, and the beat signal is sent to a mixer-2 which works as a phase detector, through a band pass filter(BPF). In the mixer-2, the input signal is mixed with the output from a crystal oscillator and the detected error voltage is introduced to VCO through LPF, dc amplifiers-1 and -2 and an integrator. The dc gain of dc amplifiers-1 and -2 are 30 dB and 20 dB, respectively. The dc gain and time constant of the integrator are 20 dB and 1 msec. The dc amplifier-2 has an additional input connected with a dc source, which determines a base frequency of VCO. The output frequency of VCO can be changed from 8 MHz to 12 MHz by varying a dc bias voltage from the dc amplifier-2. The output frequency of the crystal oscillator is 10 MHz. The loop gain of PLL(G_L) is defined by,

$$G_L = L_{M1}\ L_{M2}\ G_{A1}\ G_I\ G_{A2}\ R, \qquad (2)$$

where L_{M1} and L_{M2} are conversion losses of mixer-1 and -2, G_{A1}, G_I and G_{A2} are dc gains of dc amplifier-1 integrator and dc amplifier-2, and R is the voltage to frequency conversion ratio of VCO, respectively. Here R is about 400 kHz/V, and L_{M1} and L_{M2} are -8 dB. Eq.(2) gives G_L of 8.1×10^7 rad/sec.

When PLL is locked, it works to satisfy a frequency relation given by,

$$|f_{in} \pm f_{VCO}| = f_x, \qquad (3)$$

where f_{in}, f_{VCO} and f_x are the input frequency of PLL, the output frequencies of VCO and the crystal oscillator, respectively. According to eq.(3) and the frequency characteristics of PLL, the input frequency which is stabilized by PLL should be chosen below 2 MHz.

2.3 Lock Range of PLL

The HCN laser employed in the interferometer of JFT-2M has frequency fluctuations consisting of fast and slow changes in speed. The slow change is caused by thermal fluctuation of the laser, such as the expansion of the laser cavity and the long term change of the discharge characteristics. The fast change is related to the vibration of the laser cavity and other optical components, instability of the laser discharge and the ripple of the dc power source. After stabilizing the power supplies of two

HCN lasers, the frequency fluctuation has been reduced from about 1 MHz to 200 kHz when the laser discharge is stable. When unstable, it increases to more than 1 MHz. The period of the frequency fluctuation is about 1 kHz both in stable and unstable discharges. This period is considered to relate to the mechanical vibration of the optical components of the lasers. Therefore, PLL must follow the input frequency change more than 1 MHz at a period of 1 kHz. The slo frequency change has been stabilized by feedback control using a microcomputer[4].

The lock range is a measure of the frequency stability of PLL. It is the maximum frequency bandwidth of the fluctuation that PLL can follow stably in locked. The lock range was measured by varying the input frequency from a signal generator(SG) which was used in place of the beat frequency of two lasers. The frequency of SG, the output of the mixer-1 and the tuning voltage of VCO was monitored with a frequency counter, a spectrum analyzer and an oscilloscope. The lock range is shown in Fig.3 as a function of the input power. The lock range increases with the input power. This result is consistent with the theoretical analysis of PLL. When the input power is 10 dBm at a frequency of 700 kHz, the lock range of 1 MHz can be attained. When the input power is so weak that the lock range is narrow, it can be enlarged by raising the loop gain of PLL given by eq.(2). It should be noted here that the loop gain also determines the time response of PLL. The tuning voltage of VCO is shown in Fig.4 as a function of the input frequency. When the input frequency is varied, the output frequency of VCO changes to compensate the input frequency variation keeping PLL locked.

Figure 4 shows the characteristic performance of PLL in frequency to voltage conversion which is used in FM/PLL demodulator.

The pull-in range of PLL is shown in Fig.5 as a function of the input power. The pull-in range means the maximum frequency difference that PLL can be pulled into the locked state from the unlocked state. When the pull-in range is large enough, PLL is locked automatically as soon as it si turned on. In the present PLL circuit, the initial frequency difference between the input signal and the output from VCO should be below 170 kHz to pull PLL into a locked state. After the lock-up of PLL it can follow the frequency fluctuation up to 1 MHz as shown in Fig.4.

In order to investigate the time response of PLL, the input signal from SG was frequency-modulated. Time traces of the tuning voltage of VCO are shown in Fig.6. The tuning voltage changes synchronously with the frequency-modulated input signal. When the modulation frequency is 1 kHz, which corresponds to the period of the beat frequency fluctuation of HCN lasers, PLL can follow the frequency fluctuation of about 700 kHz stably. The frequency spectra of the output of the mixer-1 are shown in Fig.7 when PLL is unlocked and locked. The input signal is the beat frequency of two HCN lasers from a Schottky barrier diode(SBD). The width of the fluctuating spectra indicates the input frequency fluctuation. When PLL is unlocked, the beat frequency from the mixer-1 fluctuates responding to the input fluctuation shown by the left hand spectra in the figure. When PLL is locked stably, the output frequency of VCO changes in time shown in the figure. Consequently, the beat frequency from the mixer-1 is locked at 10 MHz as shown in the right hand spectra of the bottom trace. The beat frequency was stabilized for more than 2 hours when the instability of the laser discharge, such as the arcing at the cathode, did not occur. The frequency resolution of the beat signal is as good as less than 10 kHz. The threshold power that the receiver of the scattering measurement can detect is determined by the noise power of the receiver. In order to observe a weak scattered signal, the signal to noise ratio should be raised by lowering the noise power. The receiver noise can be decreased by using mixers and amplifiers with low noise figure or by narrowing the bandwidth of the receiver. In the scattering measurement the signal to noise ratio increases correspondingly if the frequency resolution of the receiver can be raised without any decrease of the detected power. Therefore, the high frequency resolution is preferable in the scattering measurement.

3. Application to scattering experiment

The high frequency resolution of the receiver requires a high frequency stability of the oscillators as mentioned before. The present PLL circuit can be applied to the heterodyne detection in HCN laser scattering experiment. It can stabilize the beat frequency of two HCN lasers for more than 2 hours and its frequency resolution is less than 10 kHz as shown in previous section. The receiver system of HCN laser scattering is shown in Fig. 8 schematically. The scattered signal from JFT-2M plasma is mixed with the reference beam from the reference HCN laser at SBD. The frequency relation of the mixed down signals is locked at 10 MHz as shown in the right hand spectra of the bottom trace. The beat frequency was stabilized for more than 2 hours when the instability of the laser discharge, such as the arcing at the cathode, did not occur. The frequency resolution of the beat signal is as good as less than 10 kHz. The threshold power that the receiver of the scattering measurement can detect is determined by the noise power of the receiver. In order to observe a weak scattered signal, the signal to noise ratio should be raised by lowering the noise power. The receiver noise can be decreased by using mixers and amplifiers with low noise figure or by narrowing the bandwidth of the receiver. In the scattering measurement the signal to noise ratio increases correspondingly if the frequency resolution of the receiver can be raised without any decrease of the detected power. Therefore, the high frequency resolution is preferable in the scattering measurement.

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$$f_s - f_r = f_p \pm f - f_r. \qquad (4)$$

where f_s is a frequency of the scattered signal, f_p and f_r are frequencies of the probe and reference lasers and f is a frequency of the density fluctuation in plasma. In the present system the beat frequency, $f_b = f_p - f_r$ fluctuates at several hundred kilohertz in time. By using PLL circuit the observed frequency of the frequency converted scattered signal is kept constant at

$$f_o = 10(\text{MHz}) \pm f. \qquad (5)$$

In the present system, the observed frequency spectra are overlapped when the frequency of waves and density fluctuations is higher than 10 MHz. This overlapping can be removed by using VCO and the second local oscillator with much higher frequencies than that of waves. In near future, the scattering experiment will be carried out in JFT-2M in order to investigate the wave absorption mechanism in ICRF heating and the effect of the density fluctuation on the tokamak confinement in H-mode discharge.

4. Summary

The frequency stabilization using PLL circuit was demonstrated. It works wel to stabilize the beat frequency of two HCN lasers. The beat frequency is stabilized for more than 2 hours at a frequency resolution of less than 10 kHz. The heterodyne receiver system using PLL stabilization can be applied to the scattering experiment in JFT-2M. In near future, HCN

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Acknowledgement

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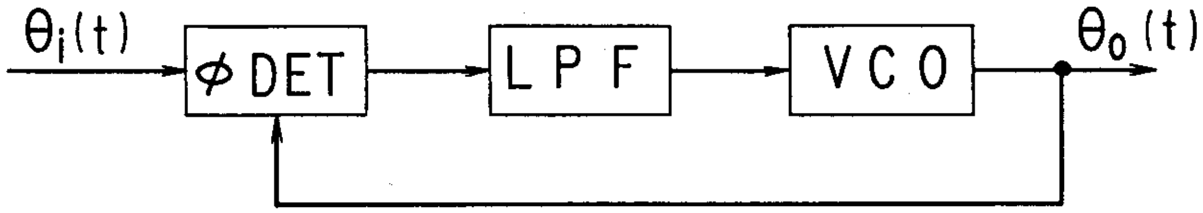

Fig.1 Block diagram of basic phase locked loop.

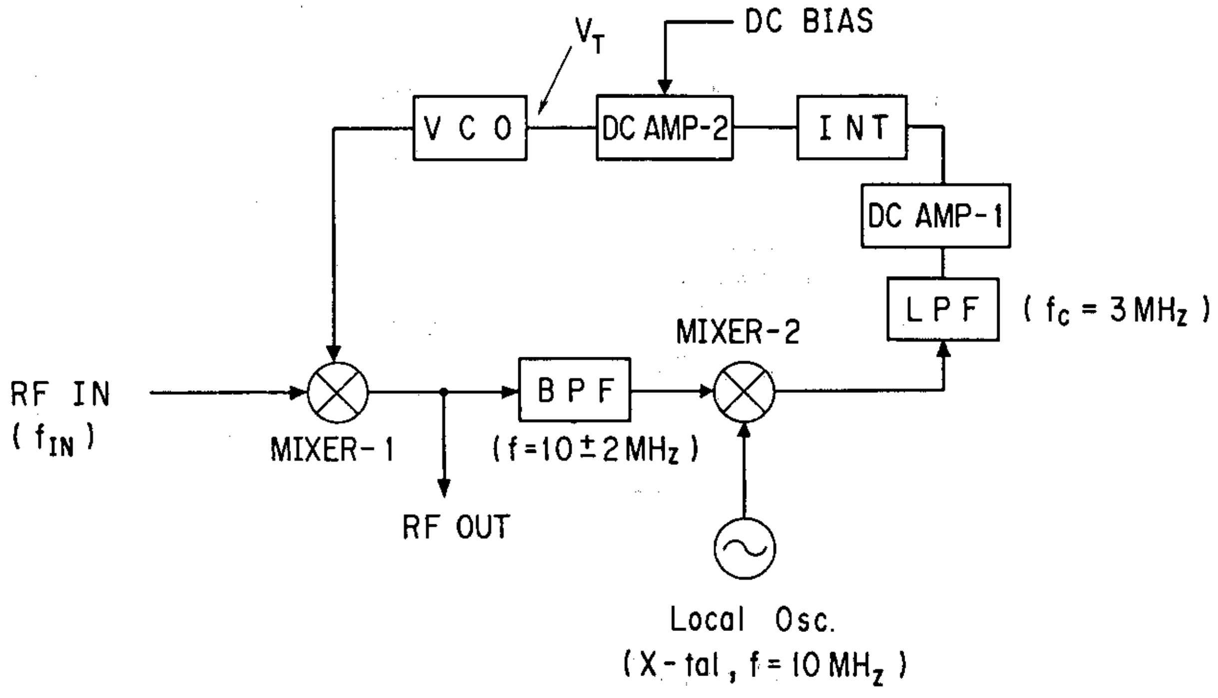

Fig.2 Block diagram of PLL circuit employed in the experiment.

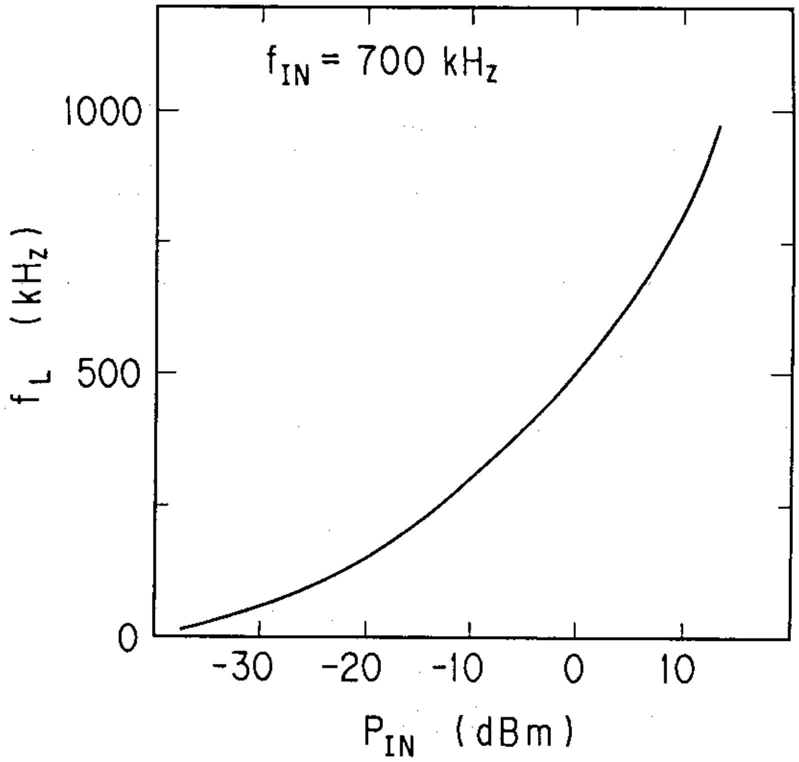

Fig.3 Lock range as a function of the input power. The input frequency is 700 kHz.

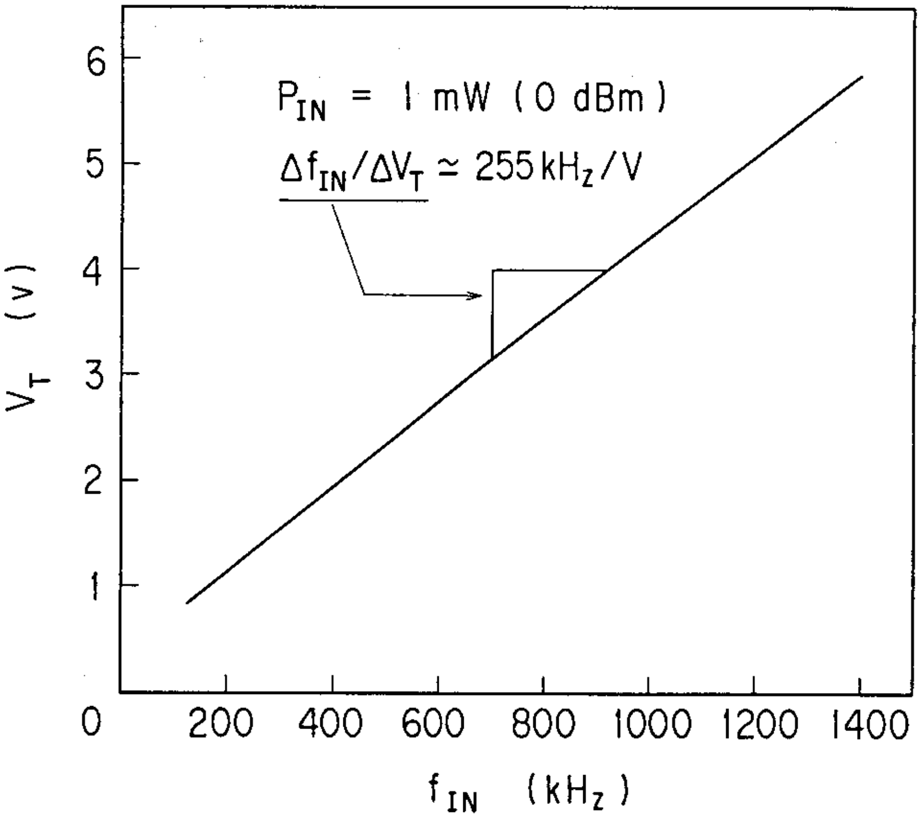

Fig.4 Characteristic performance of PLL on frequency-voltage conversion.

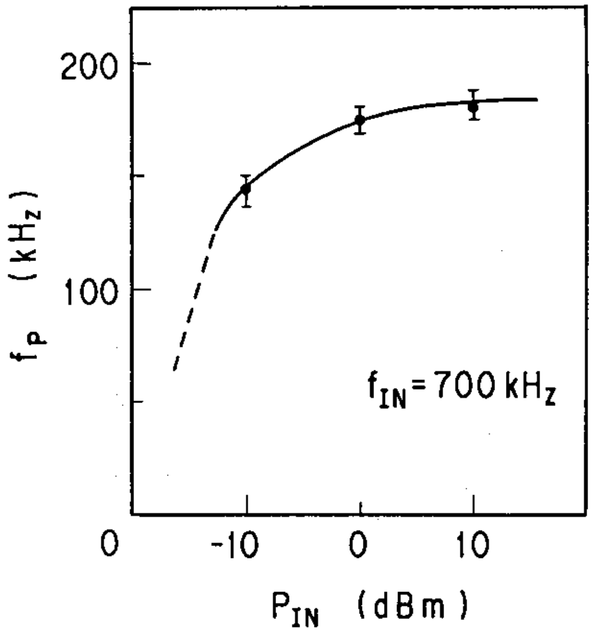

Fig.5 Pull-in range as a function of the input power. The input frequency is 700 kHz.

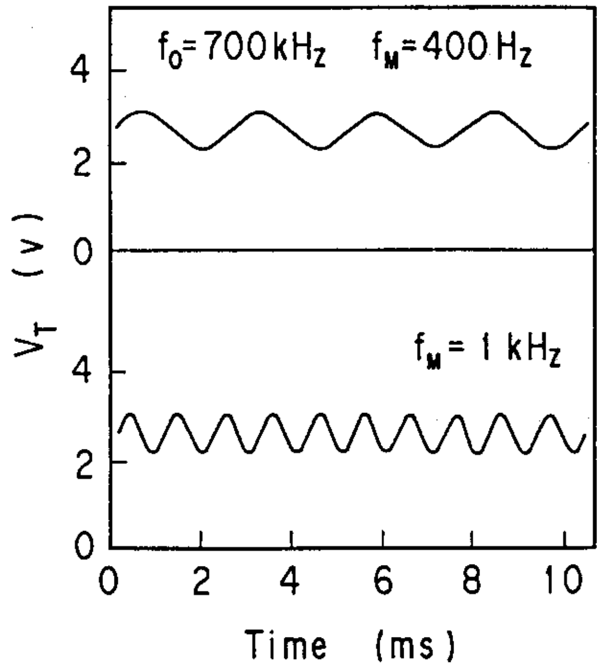

Fig.6 Time traces of the tuning voltage of VCO when the input signal from SG is frequency-modulated. The center frequency is 700 kHz and the modulation frequency is 400 Hz(top) and 1 kHz(bottom).

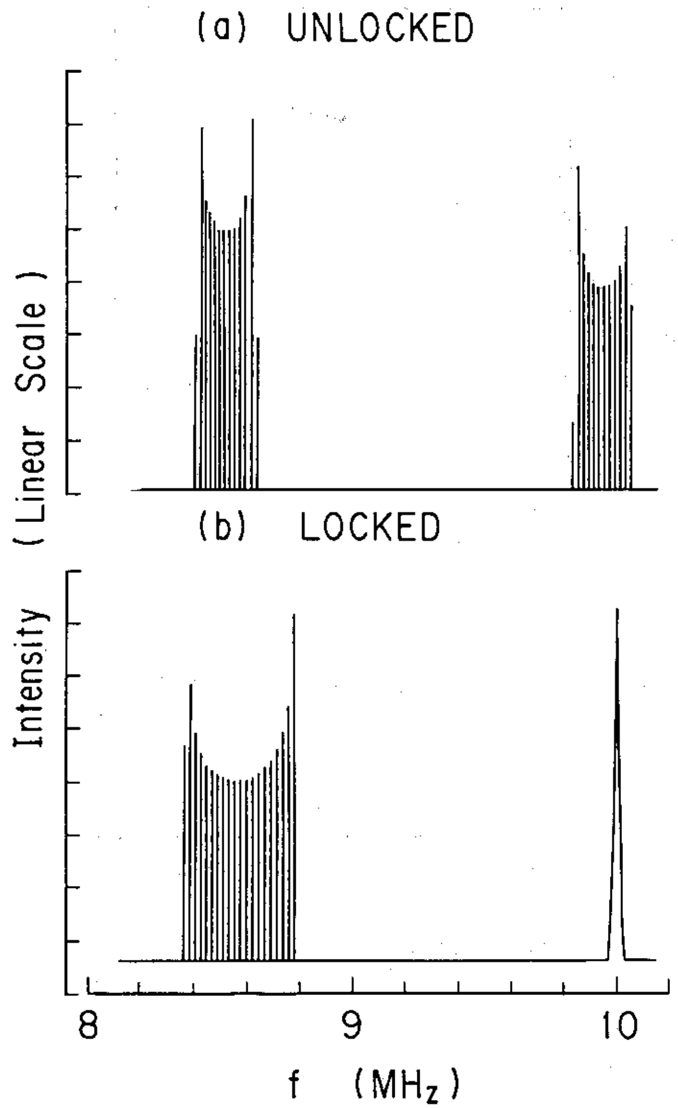

Fig.7 Frequency spectra of the beat signal from the mixer-1 observed by scanning a spectrum analyzer slowly. Top and bottom spectra are observed when PLL is unlocked and locked, respectively.

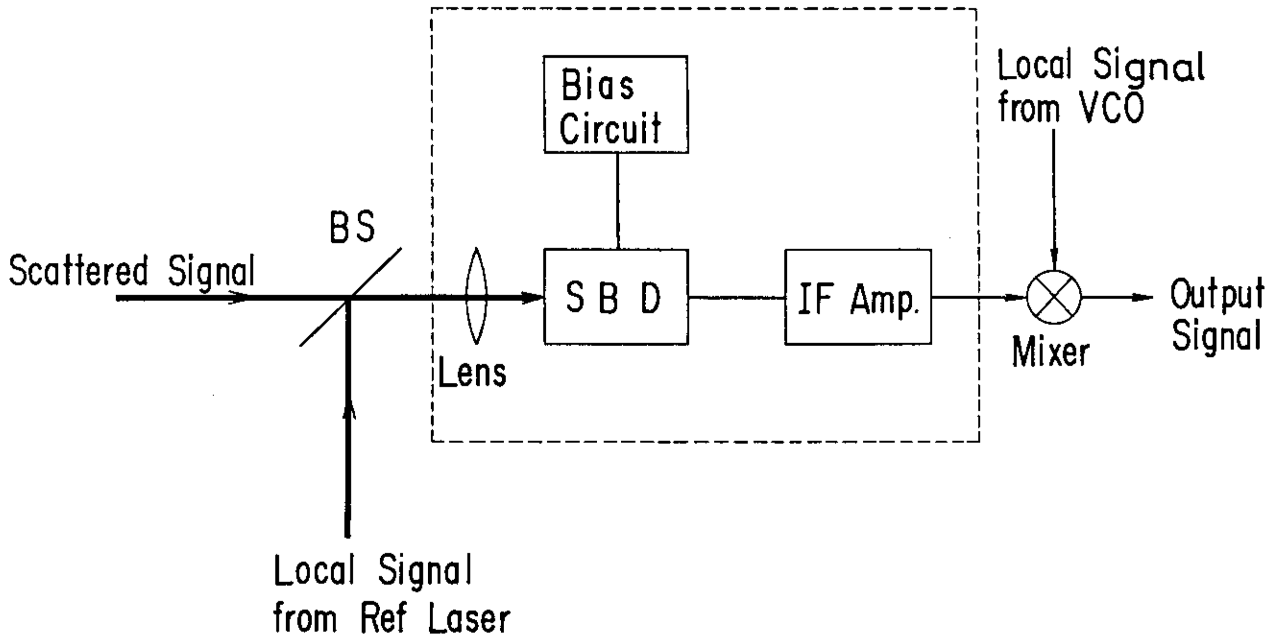

Fig.8 Schematic diagram of the receiver in HCN laser scattering experiment.