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Performance of VCO/AOM frequency shifter

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1 ABSTRACT

The NPRO-PSL is frequency offset locked to a fixed-length reference cavity. This way, the laser frequency can be tuned/controlled by changing the frequency offset, while the high frequency stability is ensured. The frequency offset generator consists of an Acousto-Optic Modulator (AOM) and its driving unit, a Voltage Controlled Oscillator (VCO) operating at a center frequency of 79 MHz. A double-pass optical configuration was chosen, and a total diffraction efficiency of 66% could be achieved. $\pm$3.3 MHz tuning range of the VCO results in a light frequency shift up to $\pm$6.6 MHz. The frequency response measurement of the AOM/VCO shows a flat frequency response within 1dB up to 1MHz. However, the phase shift due to the time delay in the AOM crystal represents a speed limiting factor. The phase noise measurement of the VCO output signal reveals that the AOM/VCO frequency shifter produces additional frequency noise on the light at the level of 18.6 mHz/rHz, and this is mainly due to the electronic noise at the input stage of the VCO oscillator. The laser beam roundness can be affected by the AOM. In our case, the beam roundness was reduced by 11%. A procedure to minimize the beam wiggle is also described here.

2 ACOUSTO-OPTIC MODULATOR

2.1. Model & Manufacturer's Specifications

2.1.1. AOM

The Acousto-Optic Modulator (AOM), Model 1205C-843 from ISOMET Corporation, was designed and optimized for the best performance as an intensity modulator, frequency shifter in the YAG wavelength region (1.06μ).

Manufacturer's Specifications

Operating Wavelength:	1.06 μm
Interaction Material:	$PbMoO_4$
Active Aperture:	0.50 mm
Center Frequency:	80 MHz
Tuned RF Bandwidth:	30 MHz
Diffraction Efficiency:	$\geq$ 80%
RF Power Input:	<1.30 W
Static Insertion loss:	$\leq$ 3.0%
Bragg Angle:	11.68 mrad

Manufacturer's Test Data

Optical Insertion Loss:	2.6%
Diffraction Efficiency:	83.7%
(at RF power 1.25 W)	

2.1.2. VCO[1]

The Voltage Controlled Oscillator (VCO) is a Model - CRO-P-AO3 Coaxial Resonator Oscillator from Synergy Microwave Corp.

Manufacturer's Specifications

Frequency Range:	750 to 850 MHz
Tuning Bandwidth:	100 MHz
Tuning Sensitivity:	5 MHz +/- 1 MHz / volt
Tuning Voltage:	1 to 24 volts DC
Bias Voltage:	12.0 VDC @ 40 mA
Output Power:	+10 dBm
Output Power Variation:	+/- 2 dB typical.
Output impedance:	50 ohms
Harmonic Suppression:	-10 dBc minimum
SSB Phase Noise:	-63 dBc/Hz @ 100 Hz offset
	-130 dBc/Hz @ 100 kHz offset
Impedance at Tuning Port:	>10 kohm
Frequency Pushing:	< 1MHz/volt
Operating Temperature:	0 to 75 deg. C.

The oscillator is divided by 10 internal to the VCO chassis. This results in an improvement of 20 dB (theoretical) in SSB Phase Noise Spec. @ 80 MHz.

1. Data provided by Rich Abbott

2.2. Optical Layout - Mode Matching

As depicted in Fig.1, the circularized laser beam (by means of two cylindrical lenses) from the LWE 126 laser is focused by a lens of f=20mm to obtain a beam waist w_0 = 0.15 mm at the center of the AOM. A concave mirror is used as a retro-reflector to realize the double-pass operation. Setting the AOM at the center of the mirror curvature R=30 cm ensures the laser beam double passing through the AOM does not change its direction with varying RF driving frequency. The reflected laser beam has a waist size of w_1=0.137 mm, and is located 275 mm apart from the retro-reflector. The vertically polarized input laser beam rotates its polarization into horizontal when it is reflected by the reflector and passes through the λ/4 wave plate again, so the output beam can be separated from the input beam by the polarizing beam splitter.

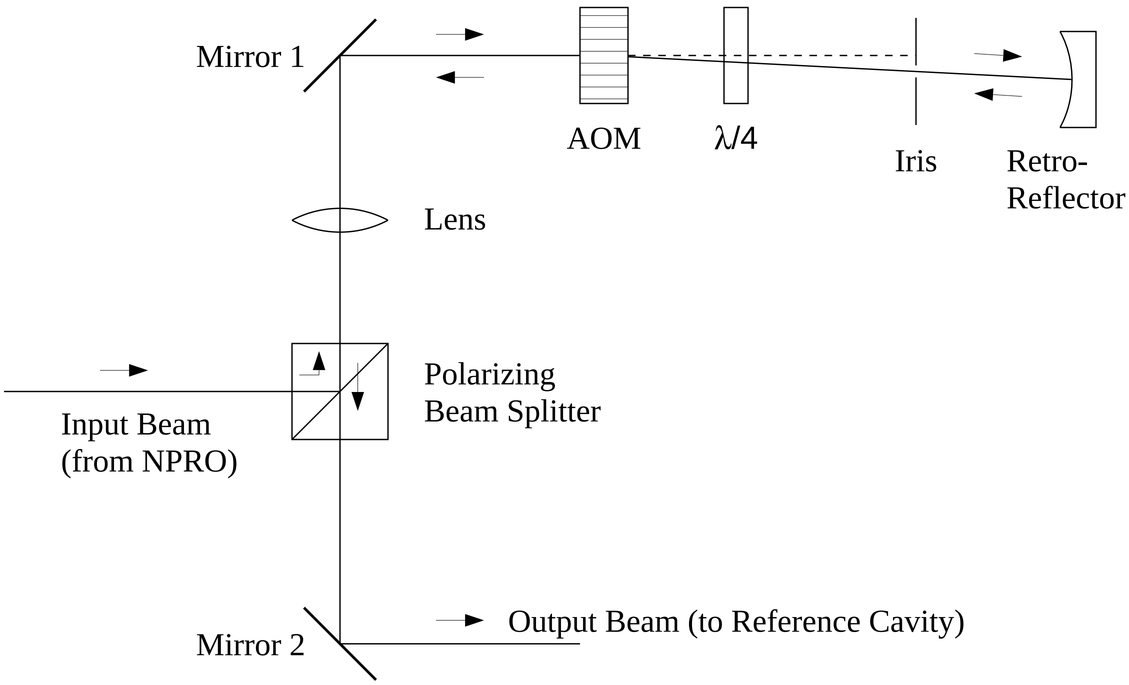

Fig. 1 AOM Frequency Shifter: Optical Layout of a Double-Pass Configuration

2.3. Diffraction Efficiency

By carefully adjusting the position and orientation of the AOM (mounted on a NewFocus 9071 stage) with respect to the laser beam waist position and Bragg condition, a single-pass diffraction efficiency of 84% (optical insertion loss not included) at a RF driving power of 1.25 W was achieved. The input laser beam power was on the level of 26 mW. The double-pass diffraction efficiency (ratio of output laser power going into the reference cavity to the input laser power (see Fig.1), including optical insertion loss of the AOM and loses in the optical chain) was measured to be 66%. The optical insertion loss of the AOM amounted to 3.0%.

2.4. Beam Distortion

The intensity distribution cross the laser beam in horizontal and vertical directions were measured by using a optical beam profiler (BeamScan 1280, PhotonInc). The results for the input and output laser beam are shown in Fig. 2a, b, and Fig. 2c, d, respectively. It can be seen that the AOM does not change the beam profile significantly, but it impairs the roundness (b/a) of the input laser beam by about 11%. Coupling the output beam of the frequency shifter into the reference cavity, the visibility was measured to be 90.4%. When coupling the original input laser beam into the cavity directly, a visibility of 91.7% was obtained.

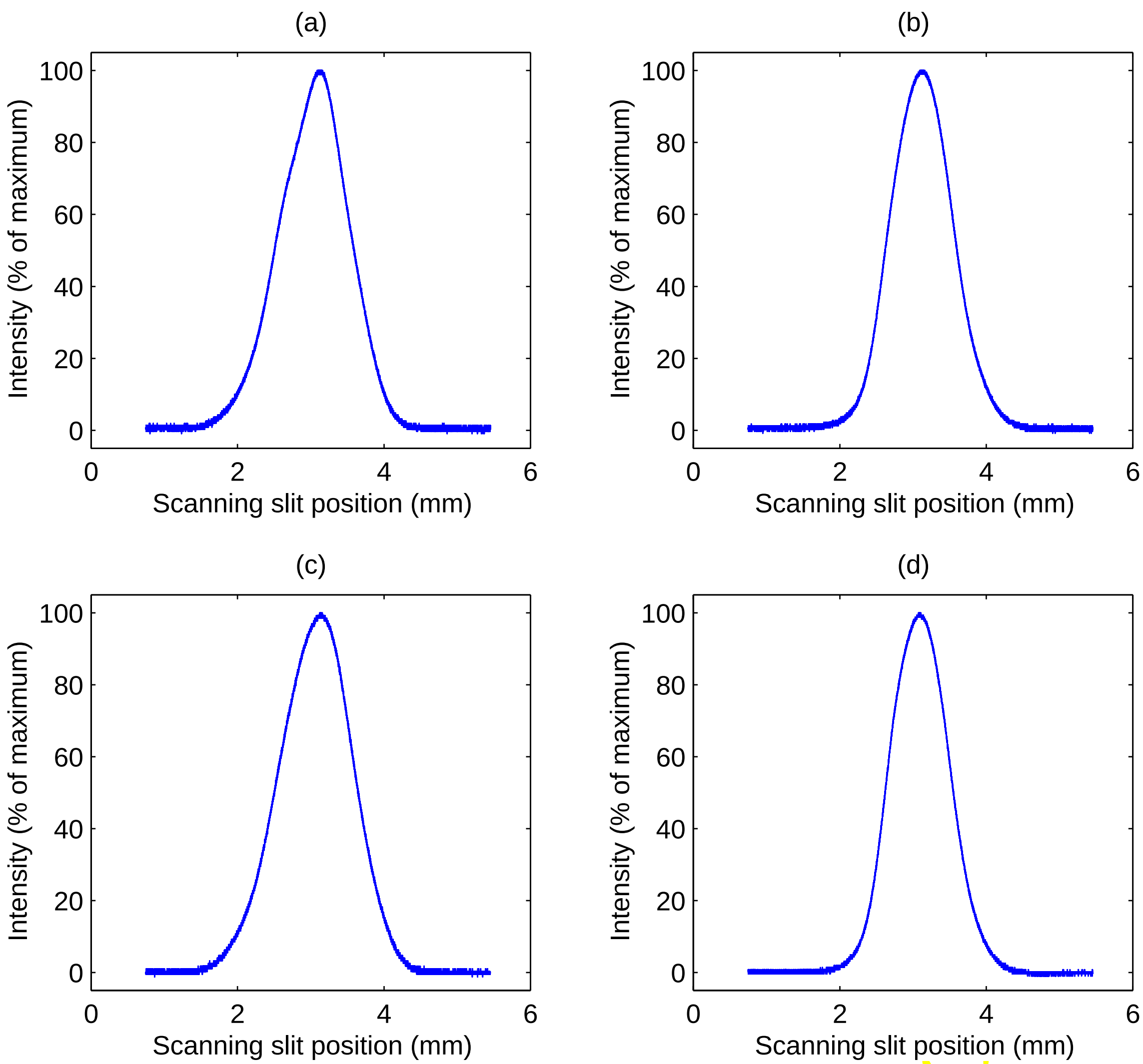

Fig. 2 Profile of the AOM Input and Output Beams

2.5. Beam Wiggle

Changing the RF driving frequency of the AOM results in both frequency change and the deflection angle change of the laser beam through AOM. The double-pass configuration not only doubles the light frequency shift but also cancels out the beam deflection, provided the retro-reflector is placed exactly in a distance of R (radius of curvature) from the AOM. For this purpose, the output laser beam is sent onto a quadrant photo detector, which detects the beam position changes. The RF signal driving the AOM is frequency modulated at a few kHz with modulation depth of about 1 MHz. The beam deflecting angle changes at the same modulation frequency. Therefore this modulation showed up in the quadrant photo detector signal. By carefully adjusting the position of the retro-reflector, and observing the photo detector signal at the modulation frequency using a signal analyzer (hp 3562A), one can find the position where the beam deflection is minimal.

By this method, the beam wiggle was minimized. The visibility (indicating the cavity coupling) did not change significantly, when the laser frequency was acousto-optically tuned over the VCO tuning range.

3 Voltage Controlled Oscillator

The Voltage Controlled Oscillator (VCO), built at Caltech (Rich Abbott), generates the RF signal to driving the AOM. It operates at a center frequency of 79 MHz and has a tuning range of +/-3.3 MHz.

Fig. 3 and 4 show the DC tuning curve of the VCO and the single side band phase noise spectrum of the VCO output.

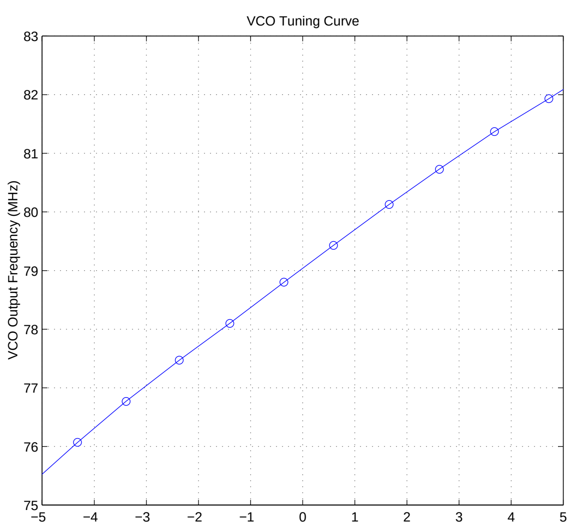

Fig. 3

DC Tuning Curve of the VCO

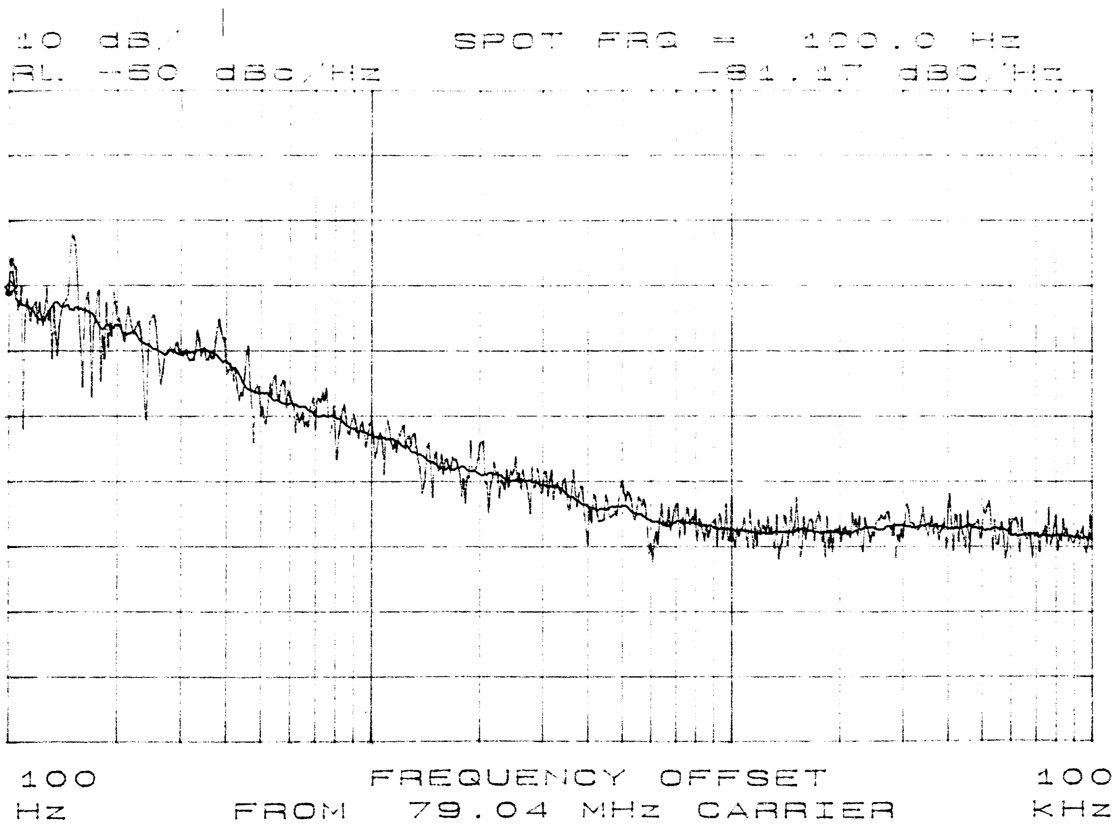

Fig. 4 Single Side Band Phase Noise of the VCO Output

3.1. Phase Noise & Limitations to Frequency Noise

The phase noise of the VCO output signal was measured against a reference RF signal generator (Marconi 2032) which has a better frequency stability. A RF mixer (MiniCircuit ZAD-1) mixes the VCO output (-1.7 dBm) and the signal (7 dBm) from the Marconi 2032 serving as a local oscillator. The mixer output at lower frequencies (<<79MHz) is proportional to the phase difference $\Delta\phi$ between the two inputs around $\Delta\phi=\pi/2$. The frequency of the reference oscillator was tuned to the VCO center frequency (with its voltage tuning input terminated). By fine tuning the Marconi frequency, the mixer output can be set to zero, meaning $\Delta\phi=\pi/2$. Due to the relative slow frequency drifts this situation can only be maintained for up to tens of seconds. One has to make sure that noise measurements are taken during the time where the mixer output is around zero voltage level. Otherwise the calibration (see below) will not be as accurate.

Another method to avoid this problem would be making a phase locked loop to lock the VCO to a reference oscillator and measure the phase noise above the unity gain frequency of the feedback loop. However, this method requires a low-noise amplifier, since one has to feedback the control signal to the VCO voltage tuning input, and the noise in the control signal will cause additional phase noise at the VCO output, and therefore falsify the measurements.

The phase noise of the VCO up to 100kHz was measured by a spectrum analyzer hp3562A, see Fig 5. The calibration of the mixer output voltage V_m versus $\Delta\phi$ was done by offsetting the Marconi frequency and recording several periods of V_m, see Fig. 6.

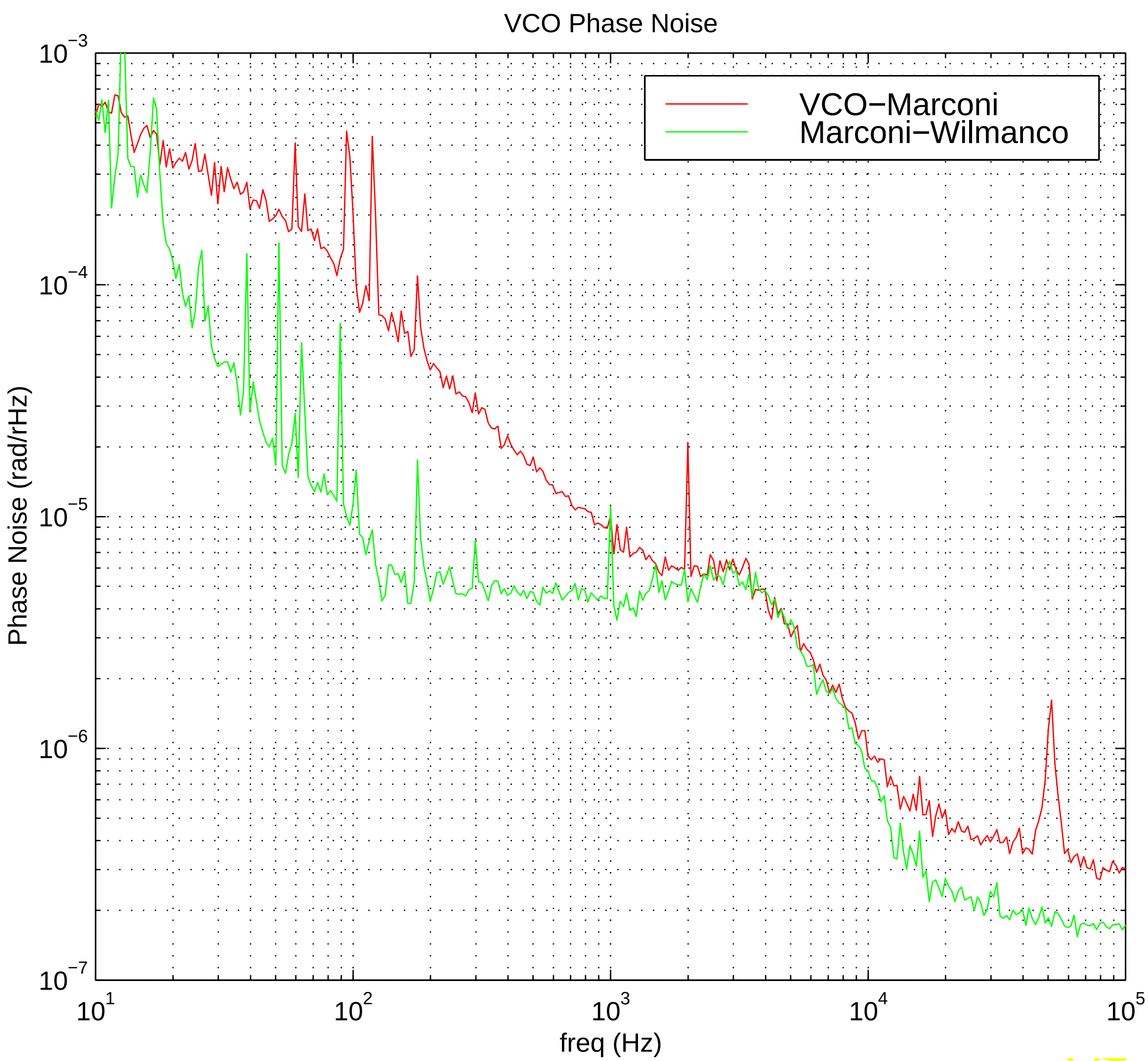

Fig. 5 VCO Phase Noise Power Spectrum

Fig. 5 shows that the phase noise falls as ~1/f, meaning the frequency noise is flat vs. f, since the frequency and phase noise (root) spectral density $N_\upsilon(f)$ and $N_\phi(f)$ are related by

$$N_\upsilon(f) = f \cdot N_\phi(f).$$

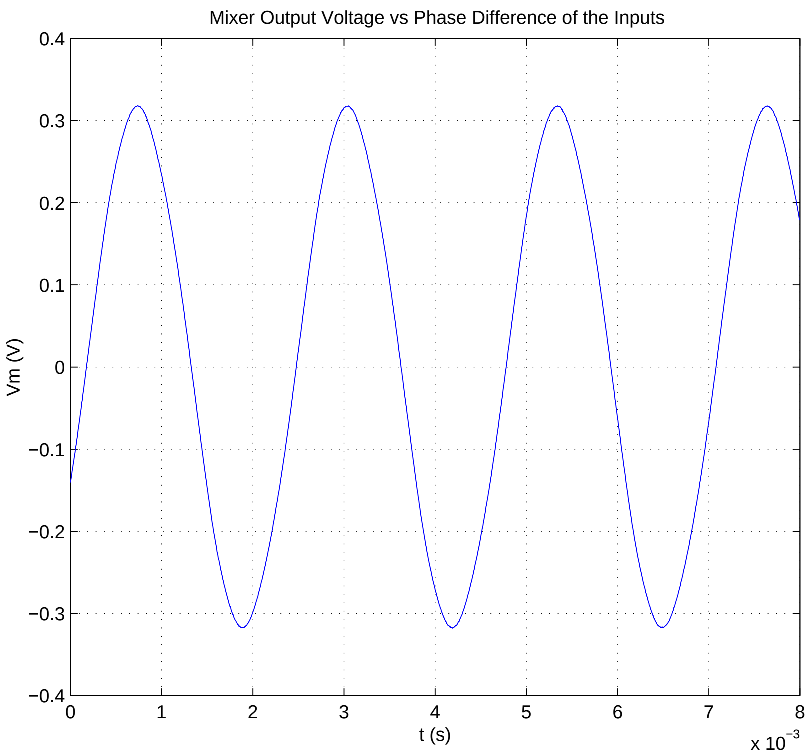

Fig. 6

Calibration Curve for the Phase Noise Measurement

The phase noise of 9.3 µrad/rHz at 1kHz corresponds to a frequency noise at the level of 9.3 mHz/rHz. This result is in good agreement with the single side band (SSB) phase noise spectrum provided by R. Abbott at Caltech, which shows that the phase noise of -103 dBc at 1 kHz offset. This corresponds to 10 µrad/rHz, using dBc = 20 log (Γ/2) where Γ is the phase modulation index (Γ<<1) in radians to convert the dBc/Hz and rad/rHz units. In our case, the rms of the phase noise, that is $\Gamma/\sqrt{2}$, has been measured. The VCO oscillator directly produces phase/frequency noise on the light through the AOM. Since the light beam double passes the AOM derived by VCO, the frequency noise on the light can be as high as 19 mHz/rHz. This number coincides with the results of frequency noise (18-20 mHz/rHz) measurements by means of the suspended 6 meter PNI cavity, see Fig. 7.

The small bump structure at about 3 kHz in Fig. 5 is due to the Marconi signal generator. This has been confirmed by measuring its phase noise against a stable 80 MHz crystal oscillator (Wilmanco VS-A-80) serving as a reference.

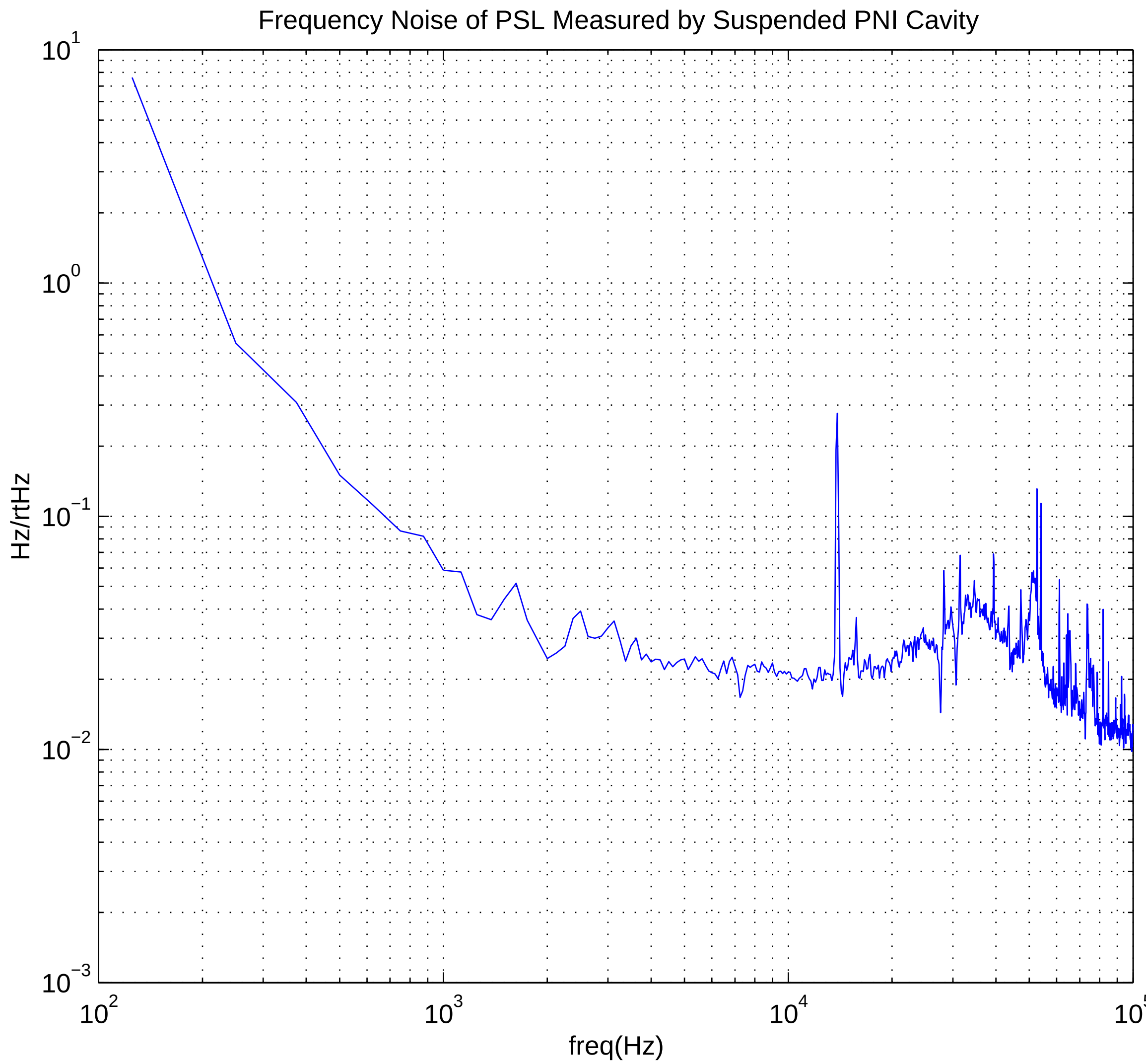

Fig. 7 Frequency Noise of PSL Measured by Suspended PNI Cavity

The voltage noise at the tuning input of the VCO has also been measured, see Fig. 8. A amplifier (Stanford SR560) was used to raise the noise level (by a factor of 1000) from the noise background of spectrum analyzer. According to the DC tuning curve (Fig. 3), the tuning sensitivity at 79 MHz (zero bias) is 625 kHz/V. This means the voltage noise at the tuning input of the VCO at the level of -98 dBV/rHz (at 1 kHz) can result in frequency noise of 16 mHz/rHz on the light (double pass). This noise source seems to be the dominate contributor to the VCO phase noise.

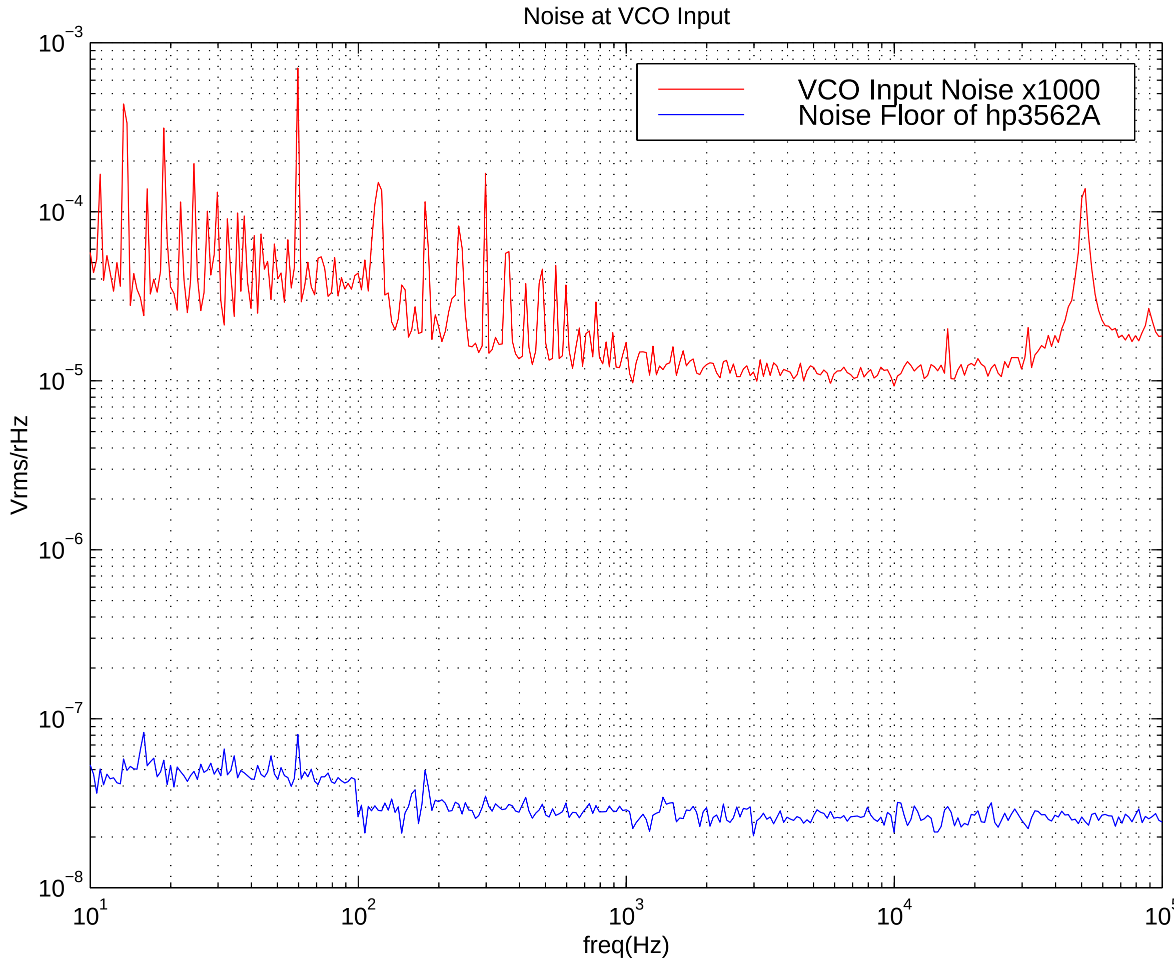

Fig. 8 Electronic Noise at the Input of the VCO

4 Frequency Response of VCO/AOM

A optical spectrum analyzer (Coherent Tropel 216) was used for measuring the frequency response of the VCO/AOM frequency shifter. The laser was frequency shifted locked to the half maximum point of a transmission peak of the spectrum analyzer cavity. The lowest possible loop gain and band width were chosen (unity gain frequency about 1 kHz) so that the frequency response measurements at higher frequencies were not affected by the feedback loop. Using a network analyzer (hp 4195), the frequency response of the frequency shifter was recorded (Fig. 9) from 1 kHz to 1 MHz, driving the VCO tuning input and measuring the error signal of the feedback control loop mentioned above. In order to remove the influence of the cavity pole (~ 300 kHz) of the optical spectrum analyzer, the network analyzer had been calibrated by means of a broadband Pockels cell phase modulator in the light path which is supposed to have a frequency response proportional to the frequency f in the region of interest (1 kHz - 1MHz). In Fig. 9 the 1/f fall is due to the calibration. Also the feature at ~ 780 kHz is from a resonance in the Pockels cell.

Taking this into consideration the frequency response curve is flat within 1 dB up to about 1 MHz. Due to the time delay (sound wave travelling through the AOM crystal), a phase shift reaches already 45 degrees at ~100 kHz. This represents a speed limiting factor in the control loop involving the AOM. But for PNI experiment, this is not going to be a restriction.

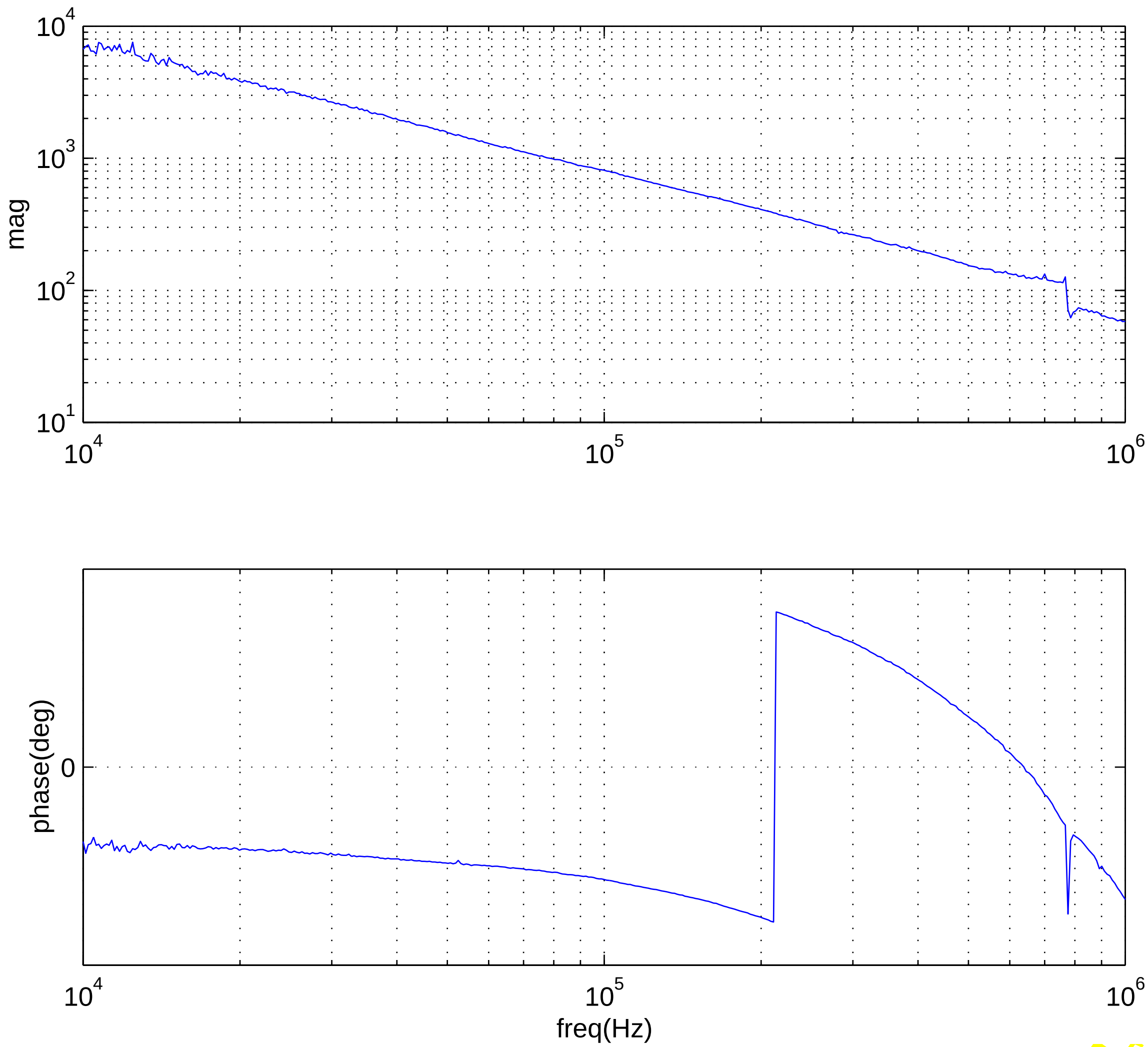

Fig. 9 Frequency Response of the VCO/AOM Frequency Shifter

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