

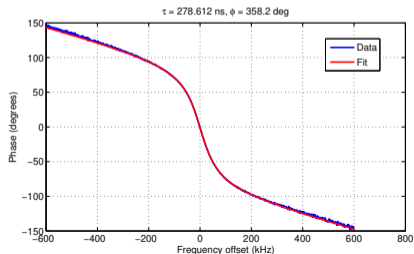
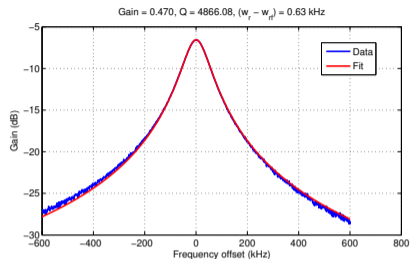
Measurement of Cavity Detuning in Storage Ring RF Systems

D. Teytelman

Dimtel, Inc., San Jose, CA, USA

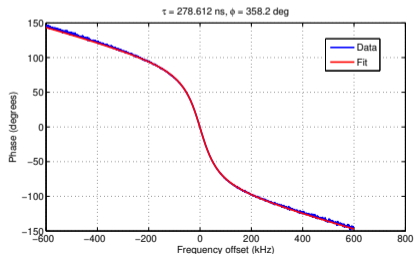
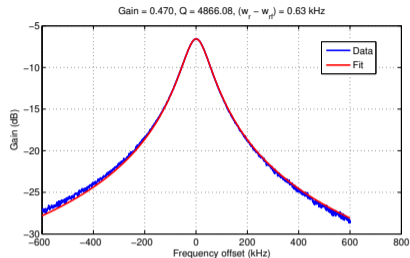
October 13, 2022

The Problem



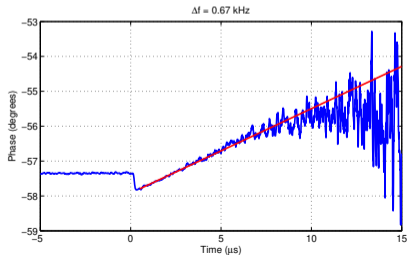
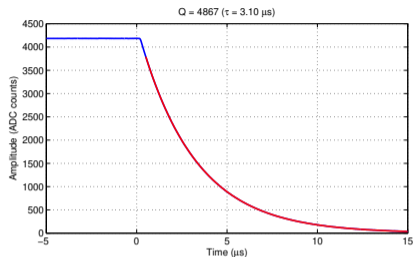
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
- Especially when the loop phase setting is not centered (-45°);
- Phase at $+45^\circ$.

The Problem



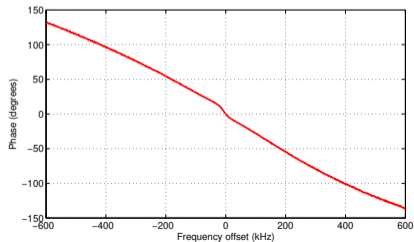
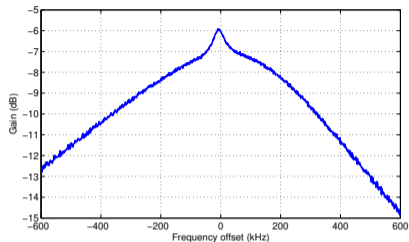
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
- Especially when the loop phase setting is not centered (-45°);
- Phase at $+45^\circ$.

The Problem



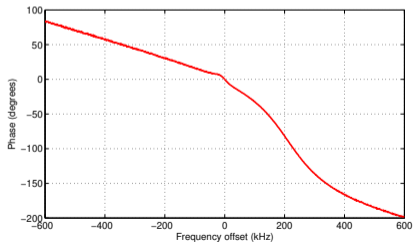
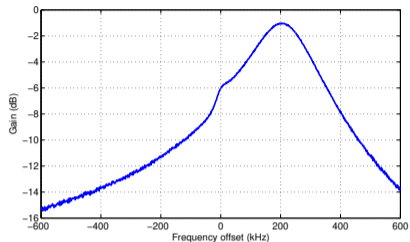
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
- Especially when the loop phase setting is not centered (-45°);
- Phase at $+45^\circ$.

The Problem



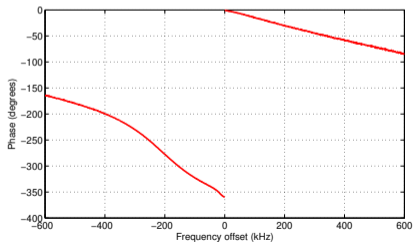
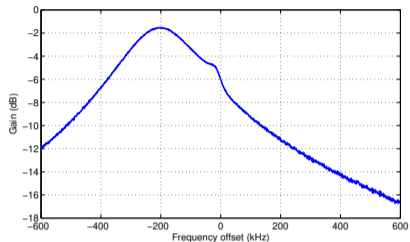
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
 - Especially when the loop phase setting is not centered (-45°);
 - Phase at $+45^\circ$.

The Problem



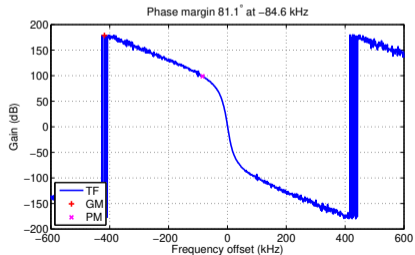
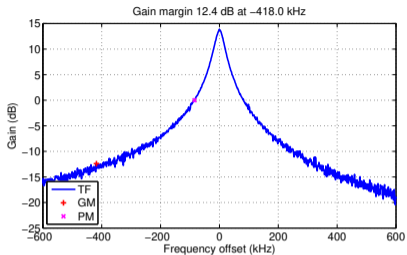
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
- Especially when the loop phase setting is not centered (-45°);
- Phase at $+45^\circ$.

The Problem



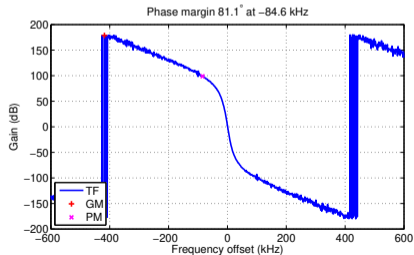
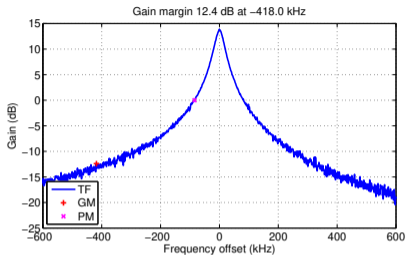
- It is easy to measure cavity tuning in the open-loop operation.
 - Loop transfer function measurement can be fitted to estimate cavity parameters;
 - Step setpoint to zero, fit the decay.
- With proportional feedback closed-loop transfer function is much wider;
- Does not tell you where the cavity resonance is, at least not precisely;
- Especially when the loop phase setting is not centered (-45°);
- Phase at $+45^\circ$.

The Motivation



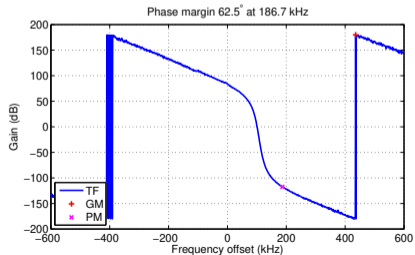
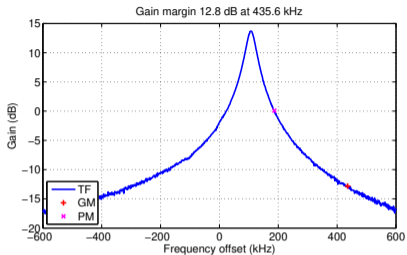
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

The Motivation



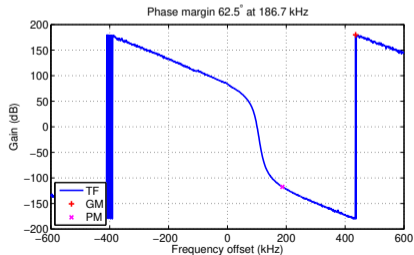
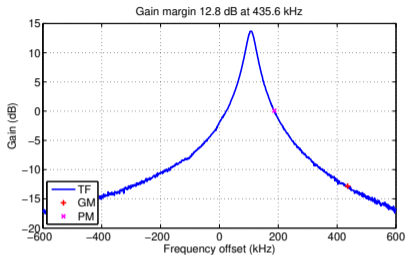
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

The Motivation



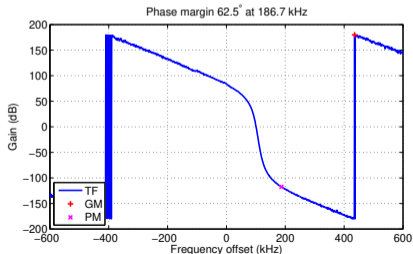
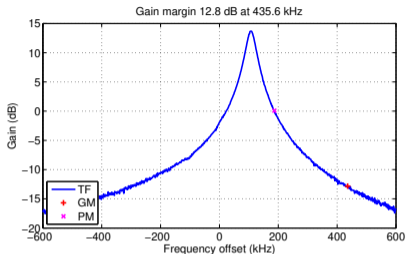
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

The Motivation



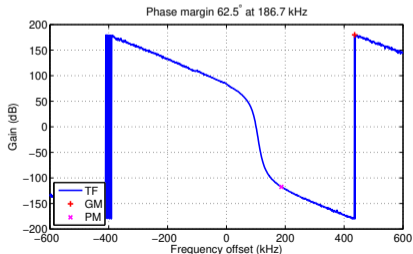
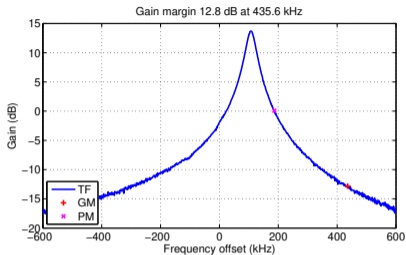
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

The Motivation



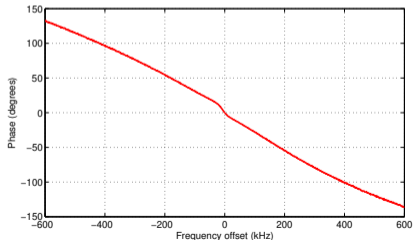
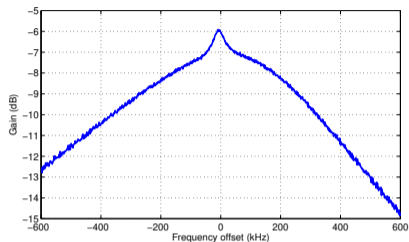
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

The Motivation



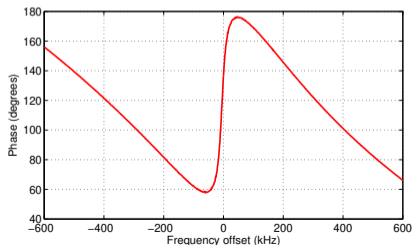
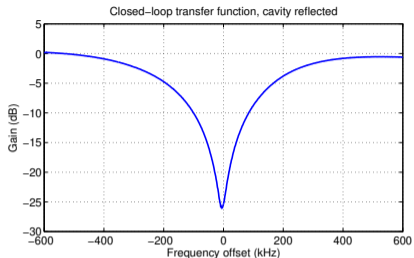
- Proportional loop is typically used in machines with high beam loading;
- Here the cavity tuned on resonance and the loop phase is centered;
- Detuning by 107 kHz (3 cavity bandwidths) reduces the phase margin by 20°;
- Cavity response “slides” on the loop delay slope, phase change of $2\pi\Delta f\tau$;
- High beam loading \rightarrow large cavity detuning;
- Measuring the detuning during operation would allow us to maintain the stability margins.

A Cause for Reflection



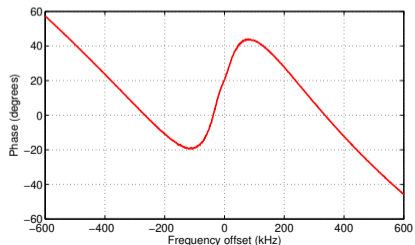
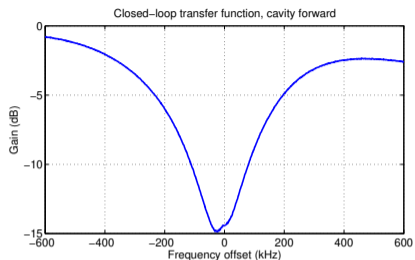
- Transfer function to the probe is not useful;
- What about the reflected power port?
- The concept — measure transfer functions to reflected and forward ports, calculate the reflection coefficient;
- Looks promising...

A Cause for Reflection



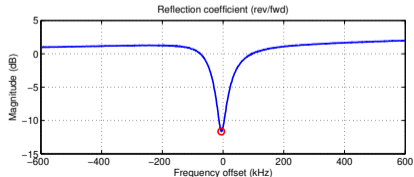
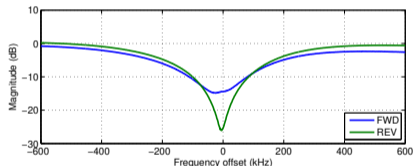
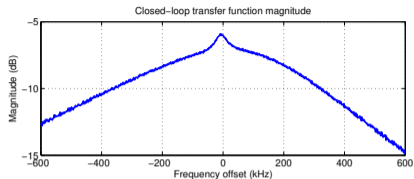
- Transfer function to the probe is not useful;
- What about the reflected power port?
- The concept — measure transfer functions to reflected and forward ports, calculate the reflection coefficient;
- Looks promising...

A Cause for Reflection

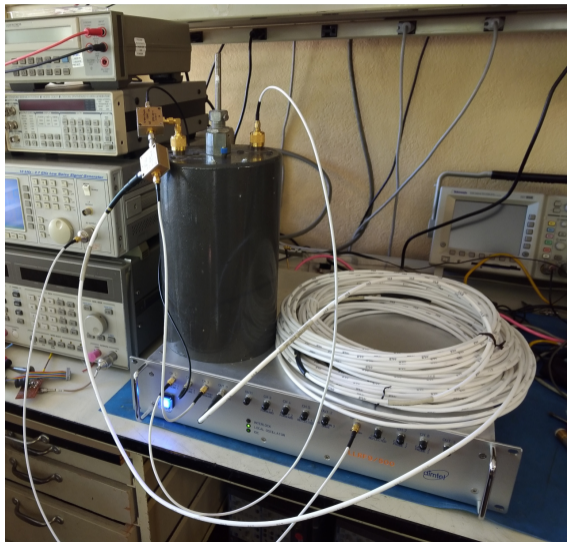


- Transfer function to the probe is not useful;
- What about the reflected power port?
- The concept — measure transfer functions to reflected and forward ports, calculate the reflection coefficient;
- Looks promising...

A Cause for Reflection

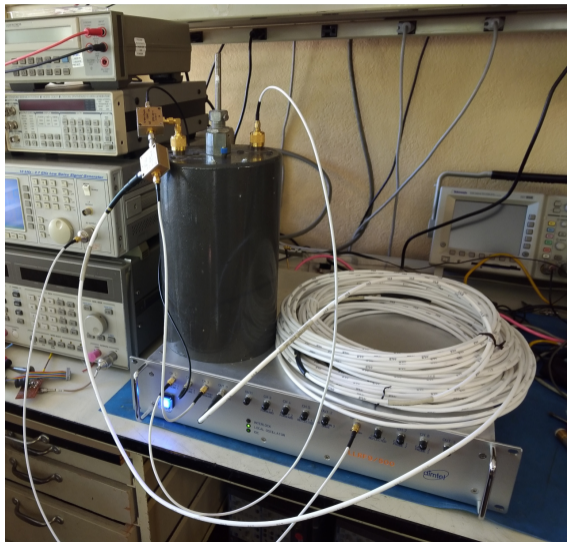


- Transfer function to the probe is not useful;
- What about the reflected power port?
- The concept — measure transfer functions to reflected and forward ports, calculate the reflection coefficient;
- Looks promising...



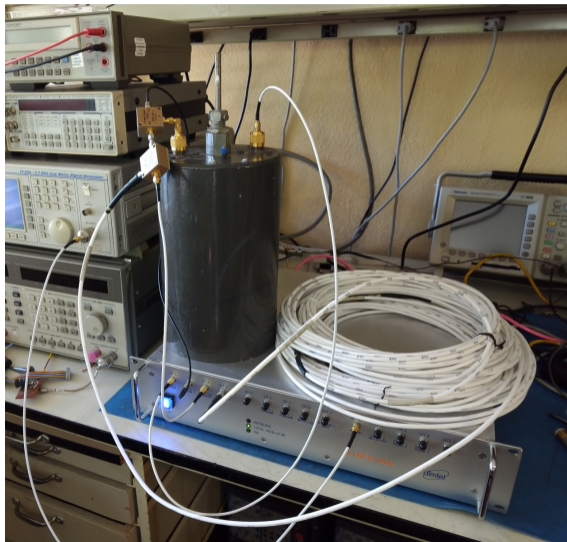
Bench Setup

- All of the following measurements are made on the bench with a cavity filter;
- $Q \approx 5000$;
- A roll of cable on the bench is to match SPEAR3 loop delay;
 - A shift register delay in the FPGA works as well, not as pretty;
- Directional couplers on the feed port to monitor forward and reflected signals.



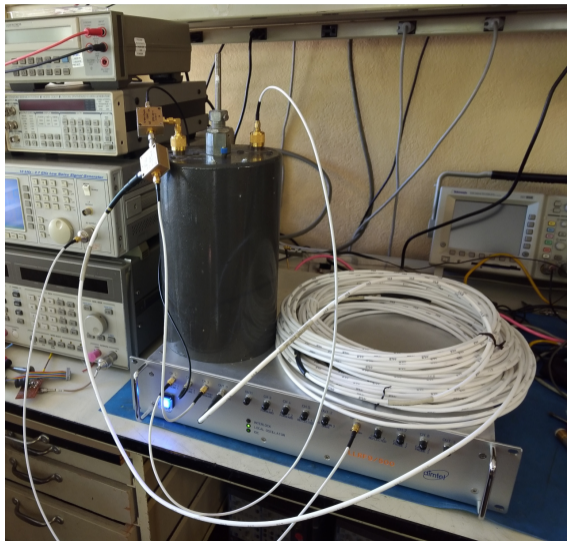
Bench Setup

- All of the following measurements are made on the bench with a cavity filter;
- $Q \approx 5000$;
- A roll of cable on the bench is to match SPEAR3 loop delay;
 - A shift register delay in the FPGA works as well, not as pretty;
- Directional couplers on the feed port to monitor forward and reflected signals.



Bench Setup

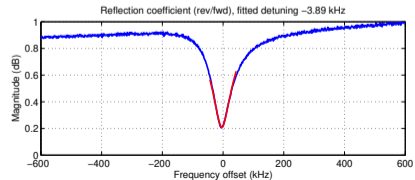
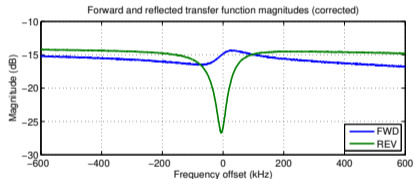
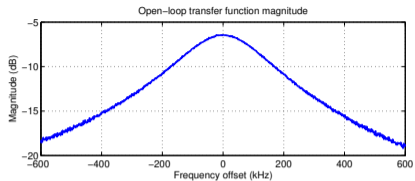
- All of the following measurements are made on the bench with a cavity filter;
- $Q \approx 5000$;
- A roll of cable on the bench is to match SPEAR3 loop delay;
 - A shift register delay in the FPGA works as well, not as pretty;
- Directional couplers on the feed port to monitor forward and reflected signals.



Bench Setup

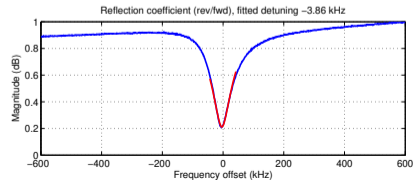
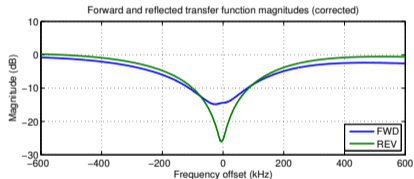
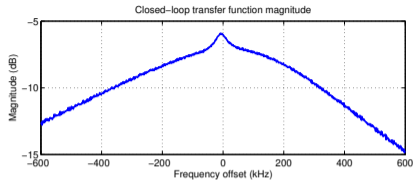
- All of the following measurements are made on the bench with a cavity filter;
- $Q \approx 5000$;
- A roll of cable on the bench is to match SPEAR3 loop delay;
 - A shift register delay in the FPGA works as well, not as pretty;
- Directional couplers on the feed port to monitor forward and reflected signals.

A Variety of Tests



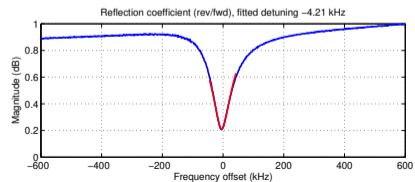
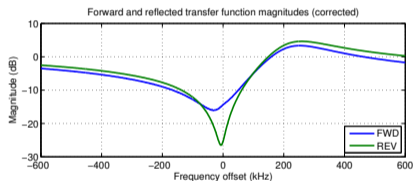
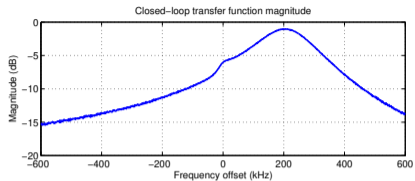
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



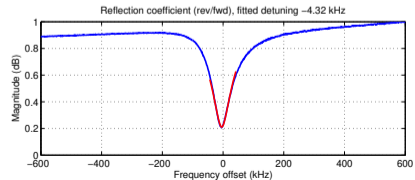
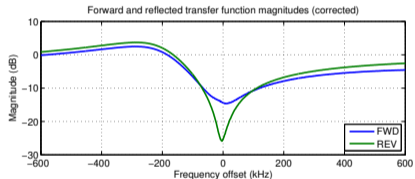
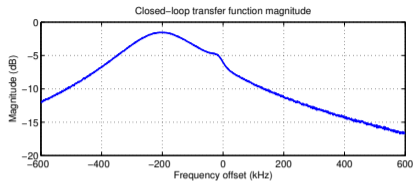
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



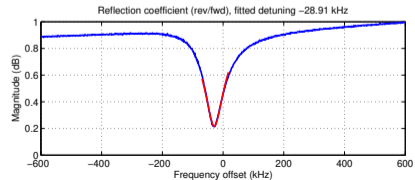
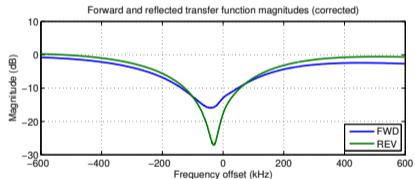
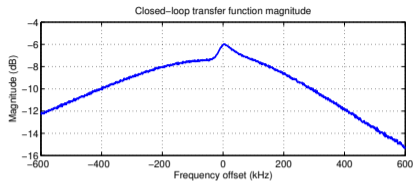
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



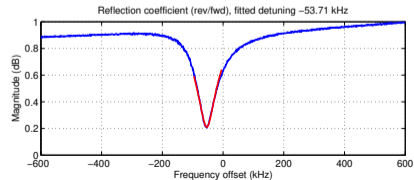
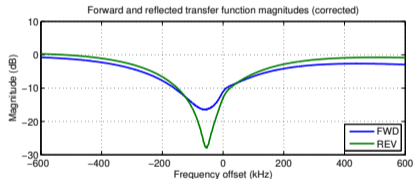
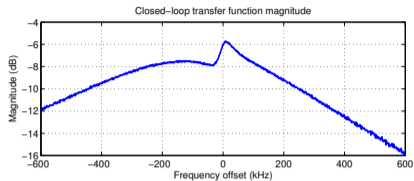
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



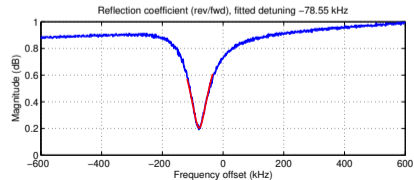
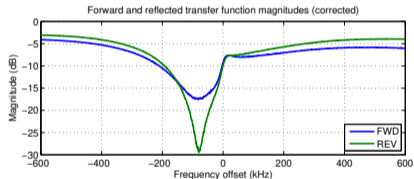
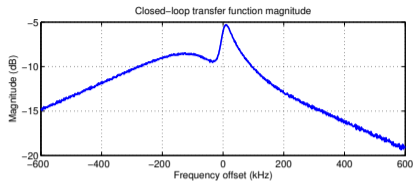
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



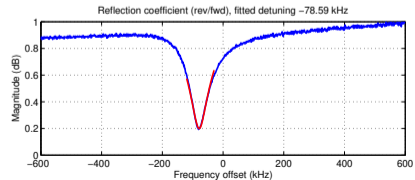
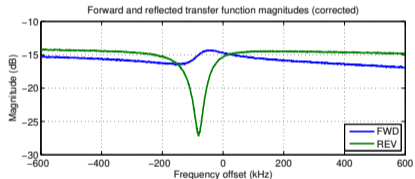
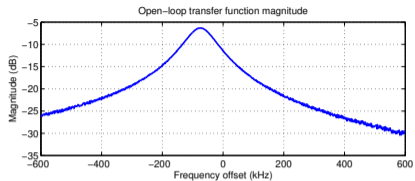
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



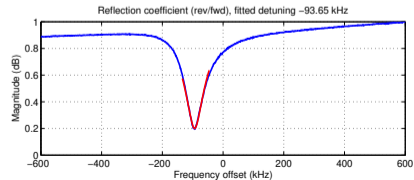
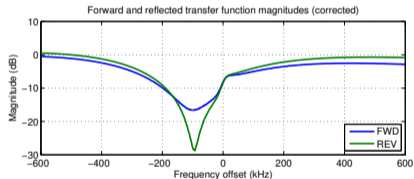
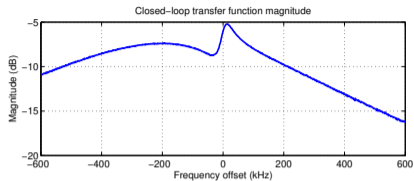
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests



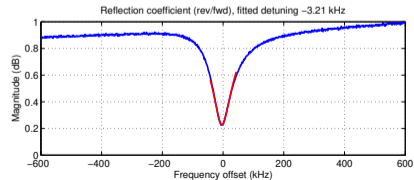
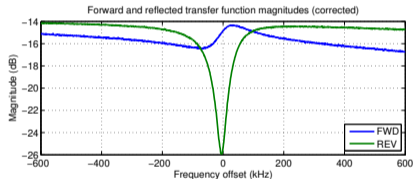
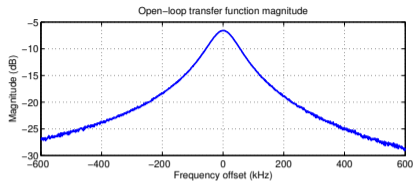
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests

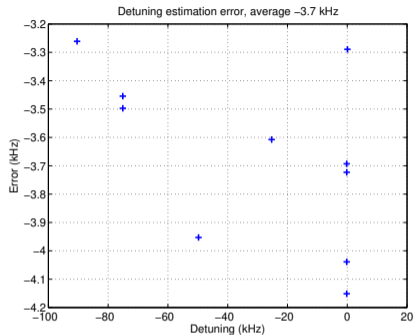


- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

A Variety of Tests

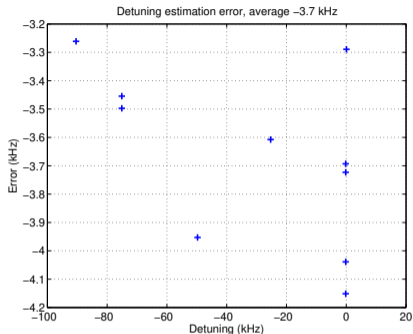


- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.



How Well Are We Doing

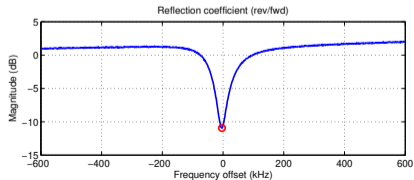
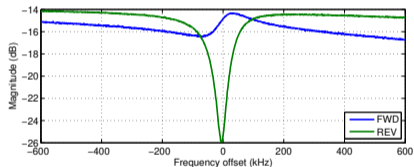
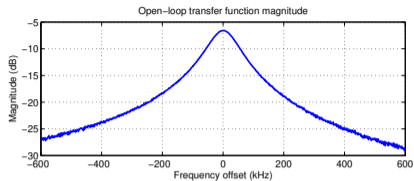
- Reasonably consistent, average error 3.7 kHz (4% of cavity bandwidth);
- The offset is easy to explain — coupler directivity;
- The reflected signal flips sign at resonance;
- Forward leakage is in phase above the resonance, out of phase below;
- The minimum moves to the left.



How Well Are We Doing

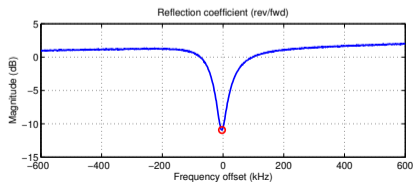
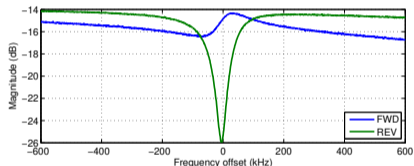
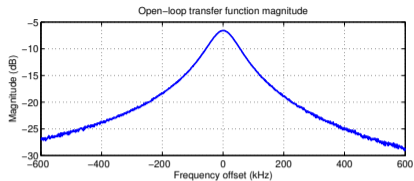
- Reasonably consistent, average error 3.7 kHz (4% of cavity bandwidth);
- The offset is easy to explain — coupler directivity;
- The reflected signal flips sign at resonance;
- Forward leakage is in phase above the resonance, out of phase below;
- The minimum moves to the left.

How Well Are We Doing



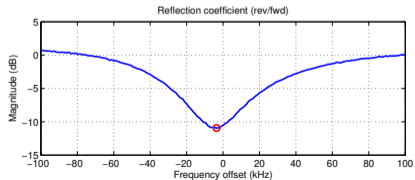
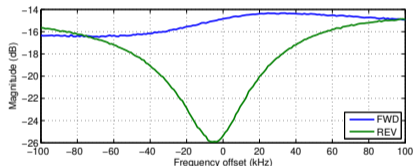
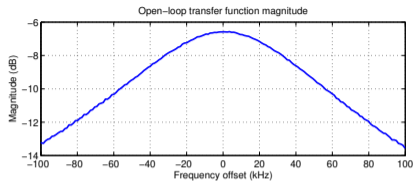
- Reasonably consistent, average error 3.7 kHz (4% of cavity bandwidth);
- The offset is easy to explain — coupler directivity;
- The reflected signal flips sign at resonance;
- Forward leakage is in phase above the resonance, out of phase below;
- The minimum moves to the left.

How Well Are We Doing



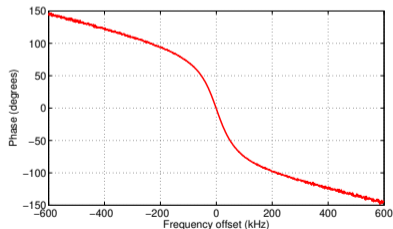
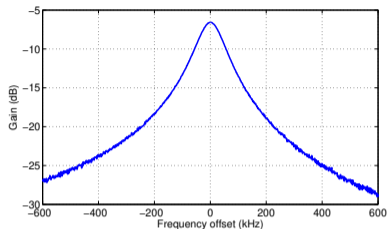
- Reasonably consistent, average error 3.7 kHz (4% of cavity bandwidth);
- The offset is easy to explain — coupler directivity;
- The reflected signal flips sign at resonance;
- Forward leakage is in phase above the resonance, out of phase below;
- The minimum moves to the left.

How Well Are We Doing



- Reasonably consistent, average error 3.7 kHz (4% of cavity bandwidth);
- The offset is easy to explain — coupler directivity;
- The reflected signal flips sign at resonance;
- Forward leakage is in phase above the resonance, out of phase below;
- The minimum moves to the left.

Directivity Correction



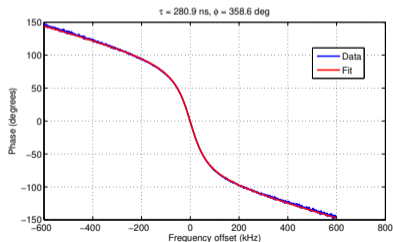
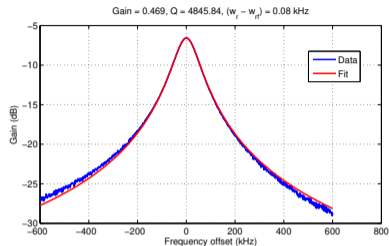
- Start from the open-loop transfer function;
- Estimate cavity parameters;
- Measure the transfer function to the drive;
- Optimize one complex coefficient to match drive and forward:

$$V_f^C = \begin{bmatrix} 1 & 0.24 - 0.15i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

- Optimize V_r reconstruction (fitting Γ):

$$\begin{bmatrix} V_f^C \\ V_r^C \end{bmatrix} = \begin{bmatrix} 1 & 0.24 - 0.15i \\ -0.04 + 0.15i & -0.4 + 0.9i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

Directivity Correction



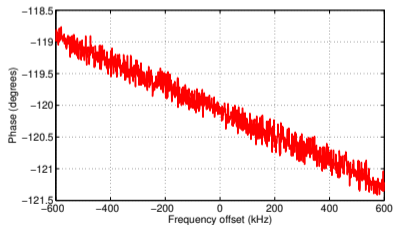
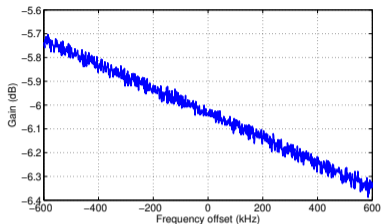
- Start from the open-loop transfer function;
- Estimate cavity parameters;
- Measure the transfer function to the drive;
- Optimize one complex coefficient to match drive and forward:

$$V_f^C = \begin{bmatrix} 1 & 0.24 - 0.15i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

- Optimize V_r reconstruction (fitting Γ):

$$\begin{bmatrix} V_f^C \\ V_r^C \end{bmatrix} = \begin{bmatrix} 1 & 0.24 - 0.15i \\ -0.04 + 0.15i & -0.4 + 0.9i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

Directivity Correction



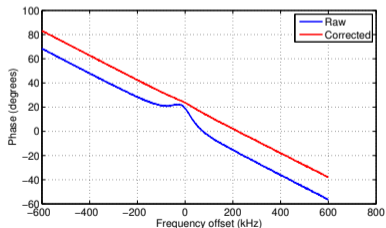
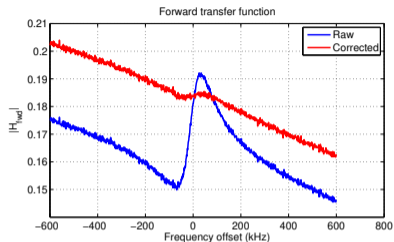
- Start from the open-loop transfer function;
- Estimate cavity parameters;
- Measure the transfer function to the drive;
- Optimize one complex coefficient to match drive and forward:

$$V_f^C = \begin{bmatrix} 1 & 0.24 - 0.15i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

- Optimize V_r reconstruction (fitting Γ):

$$\begin{bmatrix} V_f^C \\ V_r^C \end{bmatrix} = \begin{bmatrix} 1 & 0.24 - 0.15i \\ -0.04 + 0.15i & -0.4 + 0.9i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

Directivity Correction



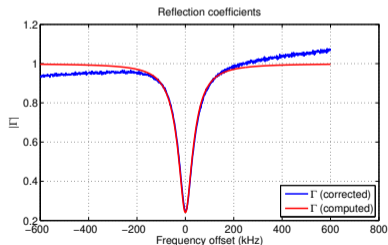
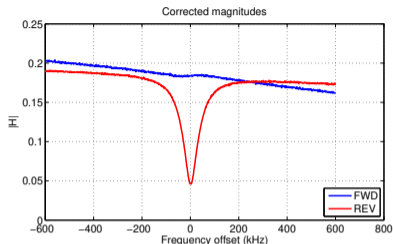
- Start from the open-loop transfer function;
- Estimate cavity parameters;
- Measure the transfer function to the drive;
- Optimize one complex coefficient to match drive and forward:

$$V_f^c = \begin{bmatrix} 1 & 0.24 - 0.15i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

- Optimize V_r reconstruction (fitting Γ):

$$\begin{bmatrix} V_f^c \\ V_r^c \end{bmatrix} = \begin{bmatrix} 1 & 0.24 - 0.15i \\ -0.04 + 0.15i & -0.4 + 0.9i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

Directivity Correction



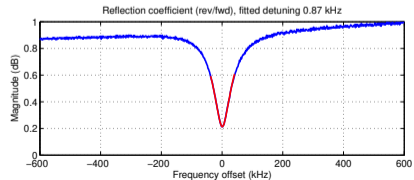
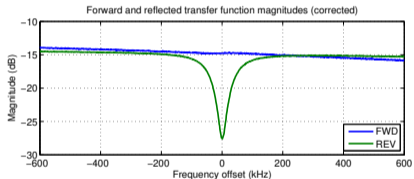
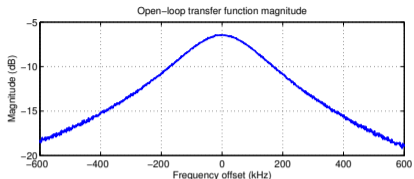
- Start from the open-loop transfer function;
- Estimate cavity parameters;
- Measure the transfer function to the drive;
- Optimize one complex coefficient to match drive and forward:

$$V_f^C = \begin{bmatrix} 1 & 0.24 - 0.15i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

- Optimize V_r reconstruction (fitting Γ):

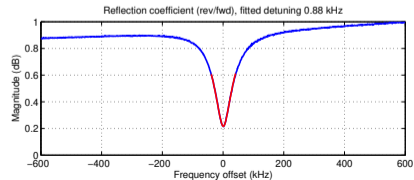
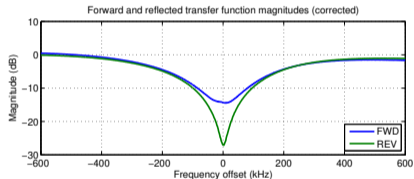
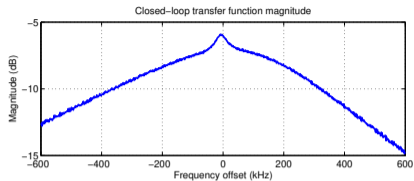
$$\begin{bmatrix} V_f^C \\ V_r^C \end{bmatrix} = \begin{bmatrix} 1 & 0.24 - 0.15i \\ -0.04 + 0.15i & -0.4 + 0.9i \end{bmatrix} \begin{bmatrix} V_f \\ V_r \end{bmatrix}$$

After Directivity Correction



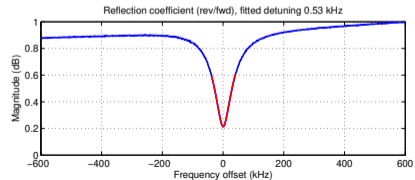
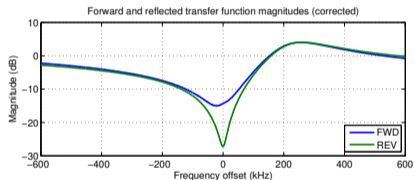
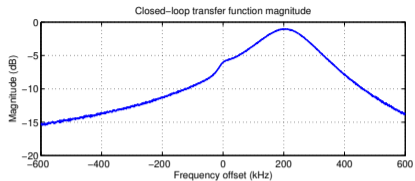
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



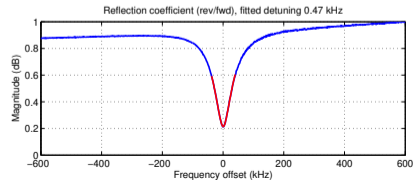
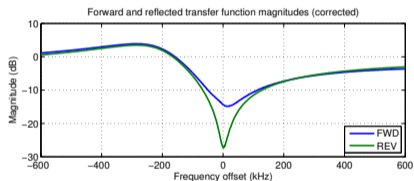
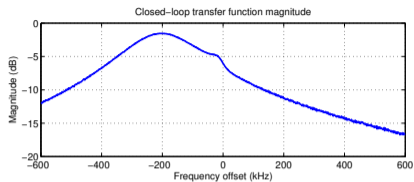
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



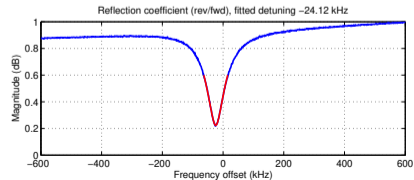
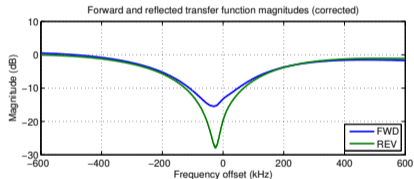
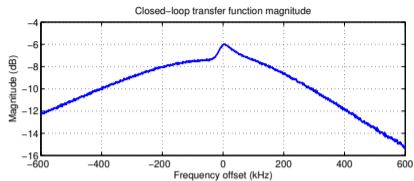
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



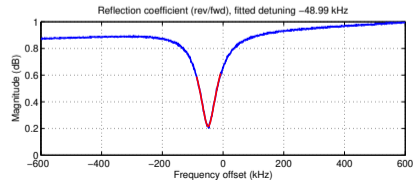
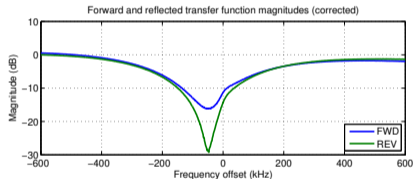
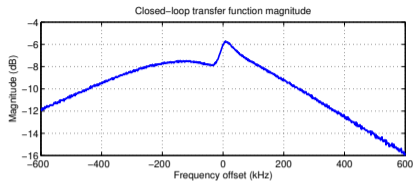
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



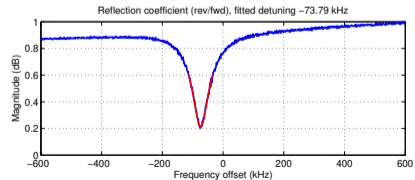
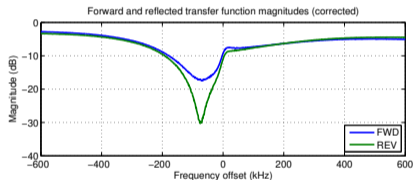
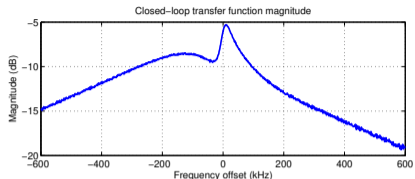
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



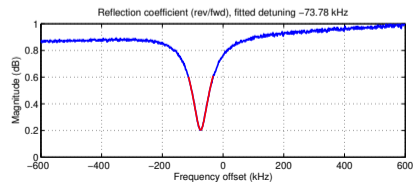
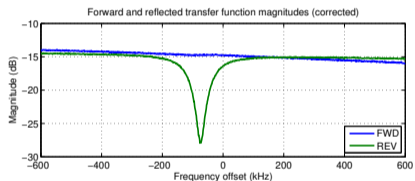
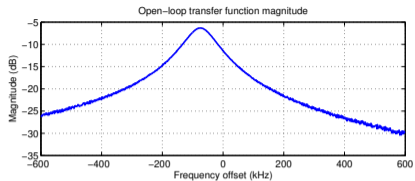
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



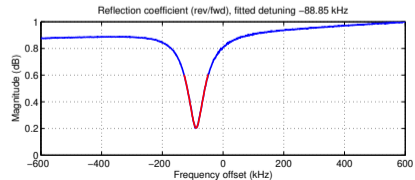
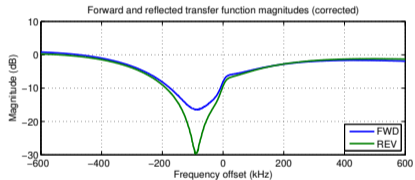
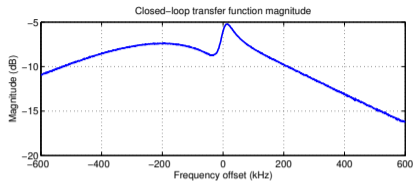
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction

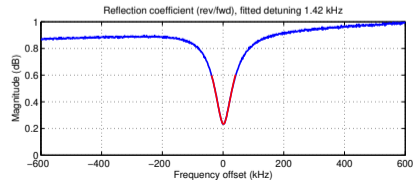
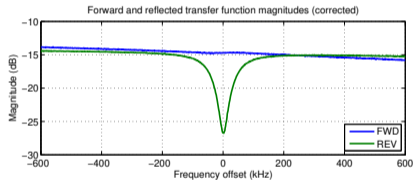
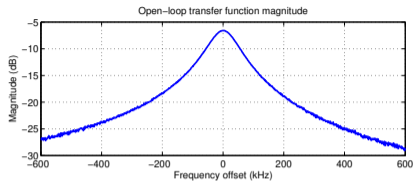


- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

After Directivity Correction



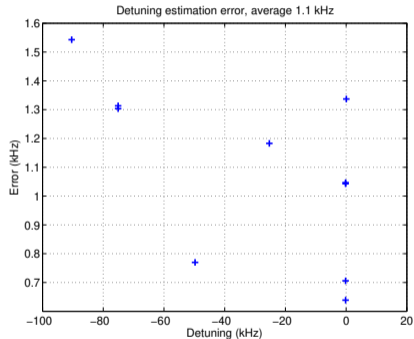
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.



After Directivity Correction

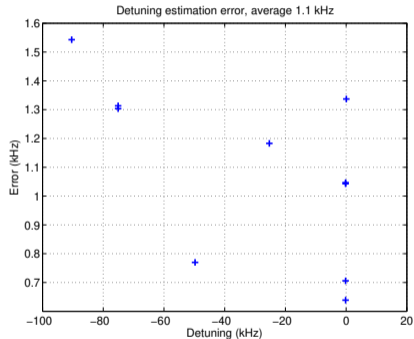
- Open-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz;
- Closed-loop, -0.2 kHz, loop phase -45°
- Closed-loop, -0.2 kHz, loop phase $+45^\circ$
- Closed-loop, -25.3 kHz;
- Closed-loop, -49.8 kHz;
- Closed-loop, -75.1 kHz;
- Open-loop, -75.1 kHz;
- Closed-loop, -90.4 kHz;
- Open-loop, on resonance.

Resonance Estimate With Coupler Correction



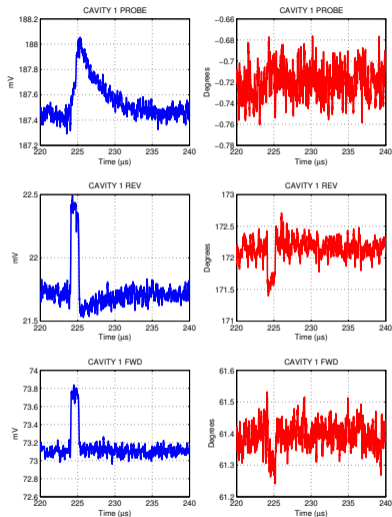
- Offset changed from -3.7 kHz to 1.1 kHz;
- Peak to peak spread of estimates is around 1 kHz.

Resonance Estimate With Coupler Correction



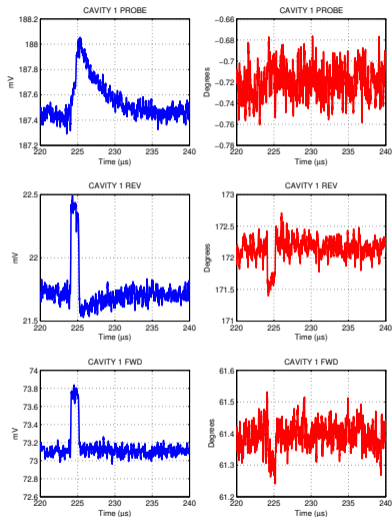
- Offset changed from -3.7 kHz to 1.1 kHz;
- Peak to peak spread of estimates is around 1 kHz.

Pulse Train Excitation — Open Loop



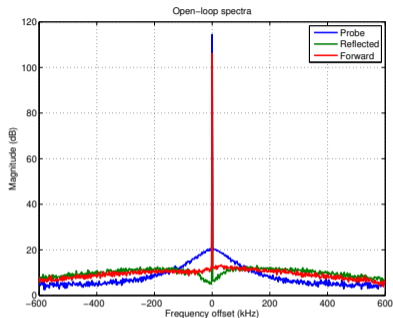
- Apply a 1.1 μs step of 1% with 555 μs period — open-loop behavior;
- Period is matched to the acquisition buffer length;
- Averaged spectra of the three cavity signals;
- Easier to see if we remove the carrier;
- Can get a somewhat noisy estimate of the reflection coefficient.

Pulse Train Excitation — Open Loop



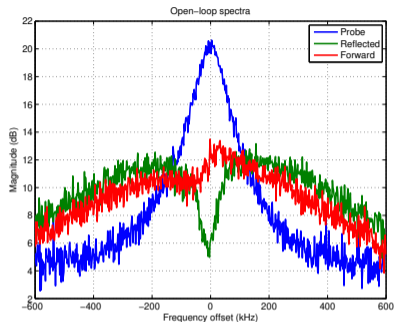
- Apply a 1.1 μs step of 1% with 555 μs period — open-loop behavior;
- Period is matched to the acquisition buffer length;
- Averaged spectra of the three cavity signals;
- Easier to see if we remove the carrier;
- Can get a somewhat noisy estimate of the reflection coefficient.

Pulse Train Excitation — Open Loop



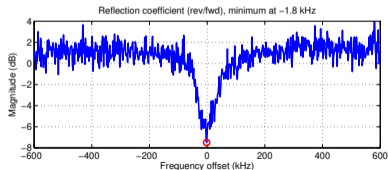
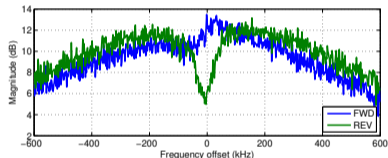
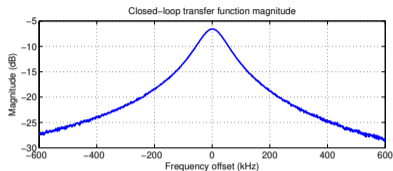
- Apply a $1.1 \mu\text{s}$ step of 1% with $555 \mu\text{s}$ period — open-loop behavior;
- Period is matched to the acquisition buffer length;
- Averaged spectra of the three cavity signals;
 - Easier to see if we remove the carrier;
 - Can get a somewhat noisy estimate of the reflection coefficient.

Pulse Train Excitation — Open Loop



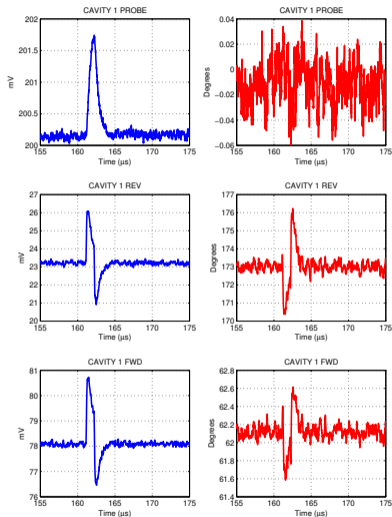
- Apply a $1.1 \mu\text{s}$ step of 1% with $555 \mu\text{s}$ period — open-loop behavior;
- Period is matched to the acquisition buffer length;
- Averaged spectra of the three cavity signals;
- Easier to see if we remove the carrier;
- Can get a somewhat noisy estimate of the reflection coefficient.

Pulse Train Excitation — Open Loop



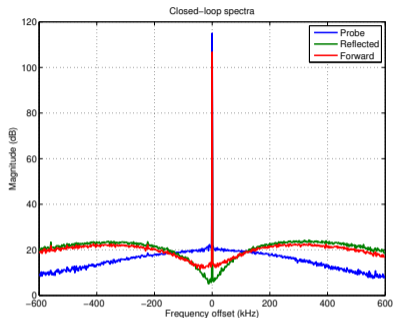
- Apply a $1.1 \mu\text{s}$ step of 1% with $555 \mu\text{s}$ period — open-loop behavior;
- Period is matched to the acquisition buffer length;
- Averaged spectra of the three cavity signals;
- Easier to see if we remove the carrier;
- Can get a somewhat noisy estimate of the reflection coefficient.

Pulse Train Excitation — Closed Loop



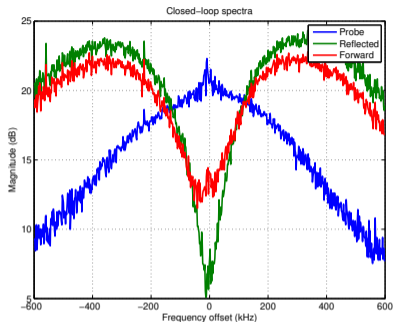
- Waveforms in the closed-loop operation;
- Averaged spectra of the three cavity signals;
- Without the carrier;
- Still usable;
- A useful tool if the three signals are monitored by physically different systems without good synchronization.

Pulse Train Excitation — Closed Loop



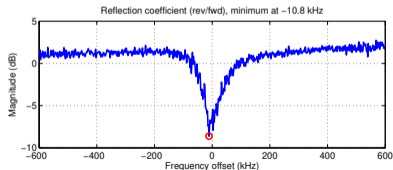
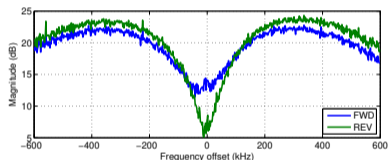
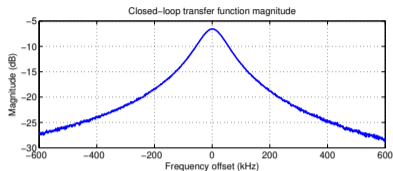
- Waveforms in the closed-loop operation;
- Averaged spectra of the three cavity signals;
- Without the carrier;
- Still usable;
- A useful tool if the three signals are monitored by physically different systems without good synchronization.

Pulse Train Excitation — Closed Loop



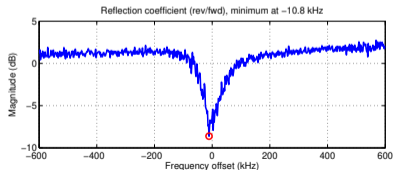
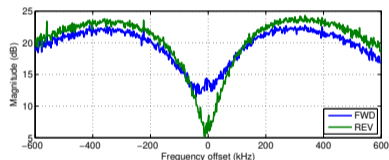
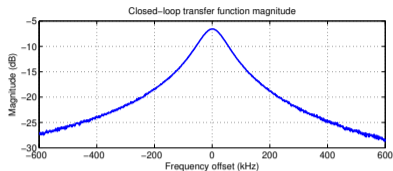
- Waveforms in the closed-loop operation;
- Averaged spectra of the three cavity signals;
- Without the carrier;
- Still usable;
- A useful tool if the three signals are monitored by physically different systems without good synchronization.

Pulse Train Excitation — Closed Loop



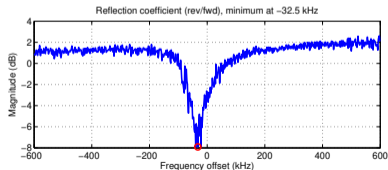
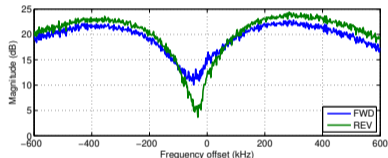
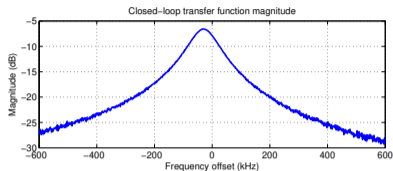
- Waveforms in the closed-loop operation;
- Averaged spectra of the three cavity signals;
- Without the carrier;
- Still usable;
- A useful tool if the three signals are monitored by physically different systems without good synchronization.

Pulse Train Excitation — Closed Loop



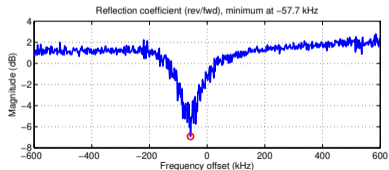
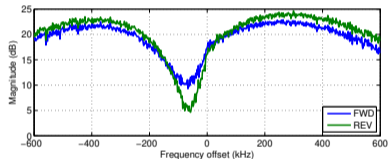
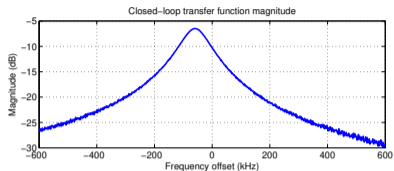
- Waveforms in the closed-loop operation;
- Averaged spectra of the three cavity signals;
- Without the carrier;
- Still usable;
- A useful tool if the three signals are monitored by physically different systems without good synchronization.

Pulse Train Excitation with Detuning



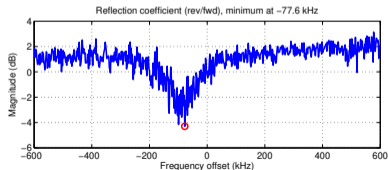
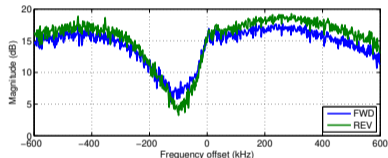
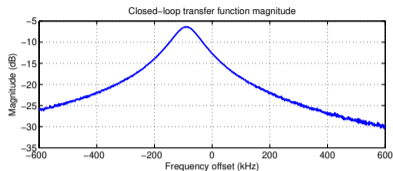
- 30 kHz detuning;
- 60 kHz detuning;
- 60 kHz detuning;
- Limited by the excitation amplitude, of course.

Pulse Train Excitation with Detuning



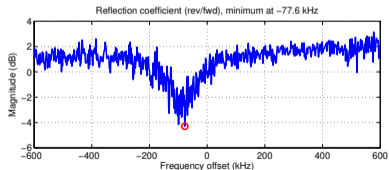
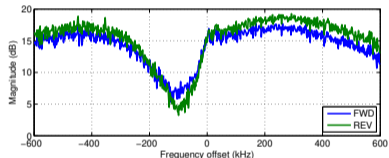
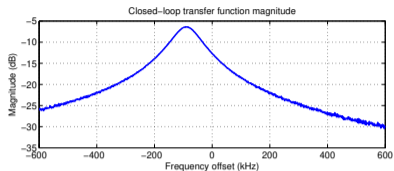
- 30 kHz detuning;
- 60 kHz detuning;
- 60 kHz detuning;
- Limited by the excitation amplitude, of course.

Pulse Train Excitation with Detuning



- 30 kHz detuning;
- 60 kHz detuning;
- 60 kHz detuning;
- Limited by the excitation amplitude, of course.

Pulse Train Excitation with Detuning



- 30 kHz detuning;
- 60 kHz detuning;
- 60 kHz detuning;
- Limited by the excitation amplitude, of course.

- Reflection coefficient provides a simple way of measuring the cavity detuning in closed-loop conditions;
- Uncorrected network analyzer measurements are sufficiently close for operational use;
- More precise estimate of detuning can be obtained with coupler directivity correction;
- Can use small excitation to extract the reflection notch from unsynchronized waveforms;
- Next step is to try this in a real machine.

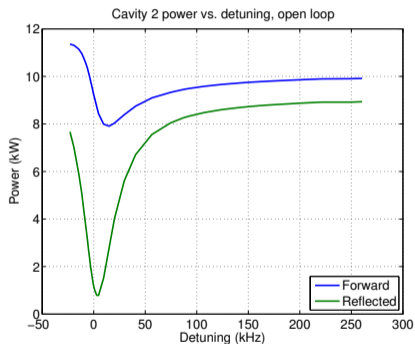
- Reflection coefficient provides a simple way of measuring the cavity detuning in closed-loop conditions;
- Uncorrected network analyzer measurements are sufficiently close for operational use;
- More precise estimate of detuning can be obtained with coupler directivity correction;
- Can use small excitation to extract the reflection notch from unsynchronized waveforms;
- Next step is to try this in a real machine.

- Reflection coefficient provides a simple way of measuring the cavity detuning in closed-loop conditions;
- Uncorrected network analyzer measurements are sufficiently close for operational use;
- More precise estimate of detuning can be obtained with coupler directivity correction;
- Can use small excitation to extract the reflection notch from unsynchronized waveforms;
- Next step is to try this in a real machine.

- Reflection coefficient provides a simple way of measuring the cavity detuning in closed-loop conditions;
- Uncorrected network analyzer measurements are sufficiently close for operational use;
- More precise estimate of detuning can be obtained with coupler directivity correction;
- Can use small excitation to extract the reflection notch from unsynchronized waveforms;
- Next step is to try this in a real machine.

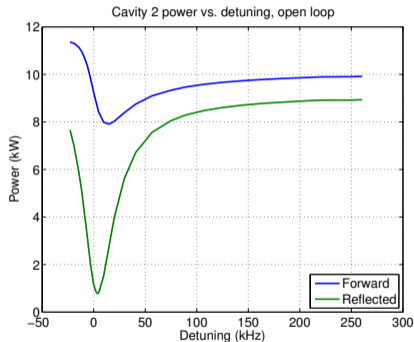
- Reflection coefficient provides a simple way of measuring the cavity detuning in closed-loop conditions;
- Uncorrected network analyzer measurements are sufficiently close for operational use;
- More precise estimate of detuning can be obtained with coupler directivity correction;
- Can use small excitation to extract the reflection notch from unsynchronized waveforms;
- Next step is to try this in a real machine.

Coupler Directivity Correction



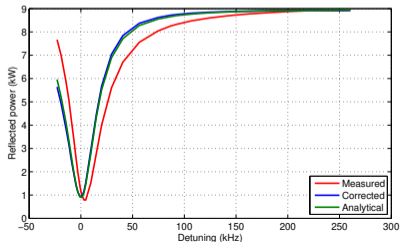
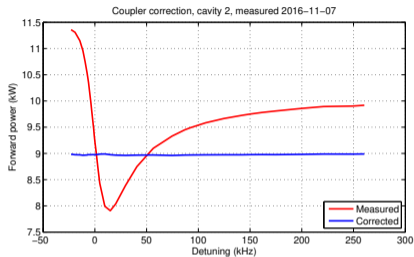
- SESAME, cavity 2;
- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
 - Remove variation in forward power;
 - Match measured and computed reflection.

Coupler Directivity Correction



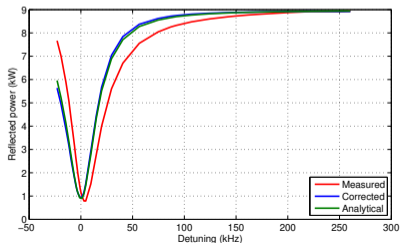
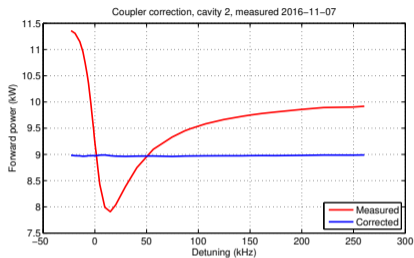
- SESAME, cavity 2;
- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
 - Remove variation in forward power;
 - Match measured and computed reflection.

Coupler Directivity Correction



- SESAME, cavity 2;
- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
 - Remove variation in forward power;
 - Match measured and computed reflection.

Coupler Directivity Correction



- SESAME, cavity 2;
- Assuming power source is matched, we compute the coupler directivity correction matrix;
- At each point, we compute the expected reflection coefficient at RF from cavity transfer function fit;
- Matrix elements are then adjusted to:
 - Remove variation in forward power;
 - Match measured and computed reflection.