Direct Measurement of the Signal Recycling Cavity Gouy Phase

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To better understand the stability of the signal recycling cavities (SRCs), it has long been our goal to measure the SRC Gouy phase to few-degree precision. Previous attempts at this measurement were indirect and required several steps measuring the radius of curvature of each optic individually, from which the ray transfer matrices determining the Gouy phase were constructed. This note describes a possible direct method of measuring the SRC Gouy phase using the co-resonance of higher-order mode (HOM) noise sidebands with the TEM_{00} carrier. The frequency separation of these resonances is linearly dependent on the Gouy phase of the cavity. This method requires a single spectroscopic measurement of the SRC reflection and can be performed while the end stations are down for upgrades.

Measurement Principle

In an axially symmetric cavity of length L, a transverse Hermite-Gauss mode TEM_{mn} is resonant when its roundtrip optical phase equals an integer number N of cycles

$$\frac{4\pi L}{c}\nu - 2(m+n+1)\phi_G - \phi_0 \quad = \quad 2\pi N \tag{1}$$

In the above equation, ν is the optical frequency, ϕ_G is the one-way Gouy phase, and ϕ_0 is the phase shift arising from reflection at the dielectric mirrors. Eq. 1 has solutions

$$\nu_{N,m,n} \quad = \quad \Delta\nu_{\mathrm{FSR}} \left[N + (m+n+1)\,\frac{\phi_G}{\pi} + \phi_0 \right] \tag{2}$$

where $\Delta\nu_{\mathrm{FSR}} = c/2L$ is the free spectral range (FSR) of the cavity.

When the TEM_{00} carrier is resonant, HOM noise sidebands are co-resonant at a frequency shift of

$$\begin{aligned} \delta\nu_{mn} &= \nu_{N,m,n} - \nu_{N,0,0} \\ &= \Delta\nu_{\mathrm{FSR}}\,(m+n)\,\frac{\phi_G}{\pi} \end{aligned} \tag{3}$$

due to the modal dependency on Gouy phase. Thus, the Gouy phase of the SRC can be directly inferred from a spectroscopic measurement resolving the FSR and the resonance of any one HOM sideband:

$$\phi_G = \frac{\pi}{m+n} \frac{\delta\nu_{mn}}{\Delta\nu_{\mathrm{FSR}}} \tag{4}$$

For an assumed SRC length of 56.01 m, $\Delta\nu_{\mathrm{FSR}} = 2.67$ MHz. Based on the theoretical one-way Gouy phase of 19°, the expected mode spacing is approximately 280 kHz. These respectively define the bandwidth and spectral resolution requirements of the measurement.

Interferometer Configuration

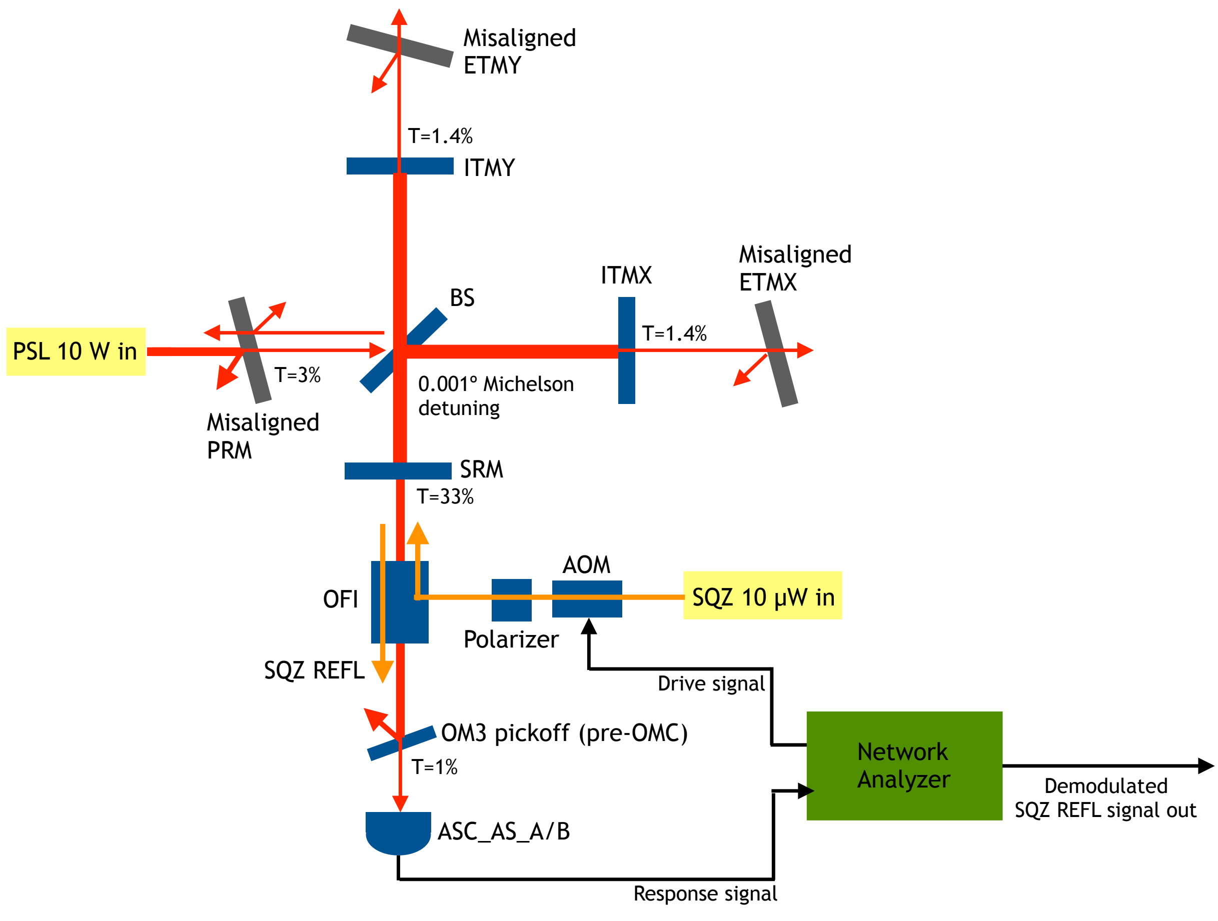

Figure 1: IFO configuration for an RF homodyne measurement of the SRC Gouy phase.

Fig. 1 shows the configuration of the interferometer (IFO) for the SRC Gouy phase measurement. The IFO is operated as a signal-recycled Michelson, with the input mode cleaner (IMC) and the SRC locked to the main pre-stabilized laser (PSL), but with the power-recycling mirror (PRM) and both end test masses (ETMs) misaligned. The active control loops are all run at their normal operating points.

The role of the PSL is only to stabilize the SRC length and the Michelson antisymmetric-port (AS) transmission, which controls the SRC finesse. For the measurement a second, auxiliary 1064 nm beam provided by the newly-installed squeezer (SQZ) is injected into the SRC from the output Faraday isolator (OFI). An RF signal generator swept in frequency from 1-4 MHz drives the SQZ AOM, which is followed by a polarizer, imprinting amplitude modulation (AM) sidebands.

In order to transfer measurable power into HOMs, the SQZ-to-SRC mode matching must be somehow degraded. Modeling indicates that this can be accomplished by a small (< 0.1 mrad) angular misalignment of TT2, the final picomotor-actuated SQZ steering mirror before the OFI. This is discussed in the following section. Another possibility is to partially occlude the SQZ beam on the ISCT6 table, provided that sufficient HOM power can be coupled into the ISCT6-to-HAM6 delivery fiber.

An RF-sensitive photodetector (RFPD) at the AS port, *before* the output mode cleaner (OMC), measures the SQZ beam reflected from the SRC. The RFPD location with highest optical sensitivity is the ASC_AS_A(B) wavefront sensor (WFS), located behind the 1% OM3 transmission pickoff. Its readout is demodulated in phase with the EOM drive signal to measure the cavity transfer function. The RF drive signal generation and demodulation can be performed using a MHz-bandwidth network analyzer, as indicated in Fig. 1.

The reflected, rather than transmitted, SQZ beam is measured because the power exiting the IFO on the symmetric port side is dominated by the back-reflected PSL beam. This is unavoidable, since, for maximum SRC finesse, the Michelson must be operated very near the dark fringe to form a highly-reflective effective mirror.

Error Analysis

The expected measurement sensitivity is estimated from a multi-mode Finesse simulation of the proposed IFO configuration (see Fig. 1), assuming the optical parameters listed in Table 1.

Parameter	**Assumed Value**	**Comment**
PSL power	10 W	Or lowest achievable
SQZ laser power	10 μW	Or highest achievable
Amplitude modulation index @ 1-4 MHz	0.1	Or highest achievable
Michelson Detuning	0.001°	Standard operating point
SRC Detuning	0.001°	Standard operating point

Table 1: Assumed parameters for the SRC optical modeling.

Fig. 2 shows the expected SRC reflection signal at the location of the ASC_AS_A RFPD, behind the 1% OM3 transmission pickoff. The curves correspond to an increasing angular misalignment of the SQZ beam injection axis into the SRC. The purple curve represents zero misalignment, which increases in 5 μrad increments up to 75 μrad (the red curve). At zero misalignment, the FSR of the cavity is clearly visible as a transmission resonance (reflection minimum) at 2.7 MHz. Misaligning the SQZ injection axis increasingly transfers power from TEM_{00} into HOMs, whose co-resonant sidebands appear as additional transmission resonances shifted in ~280 kHz intervals from the FSR. At large misalignment, the superposition of modes leads to the characteristic shape shown by the red curve, with regularly-spaced peaks aligned to the mode resonance frequencies. The object of the measurement is to precisely determine this mode spacing.

While the optical SNR suggests that the mode-splitting is measurable on a short (< 1 ms) time scale, the final SNR (and hence measurement time) additionally depends on the sensor noise of the RFPD. Only the first FSR is shown in Fig. 2. However, this pattern repeats every 2.7 MHz at comparable SNR to > 20 MHz. Thus this measurement can likely be made in a higher frequency band better-aligning with the peak sensitivity band of the RFPD, if necessary.

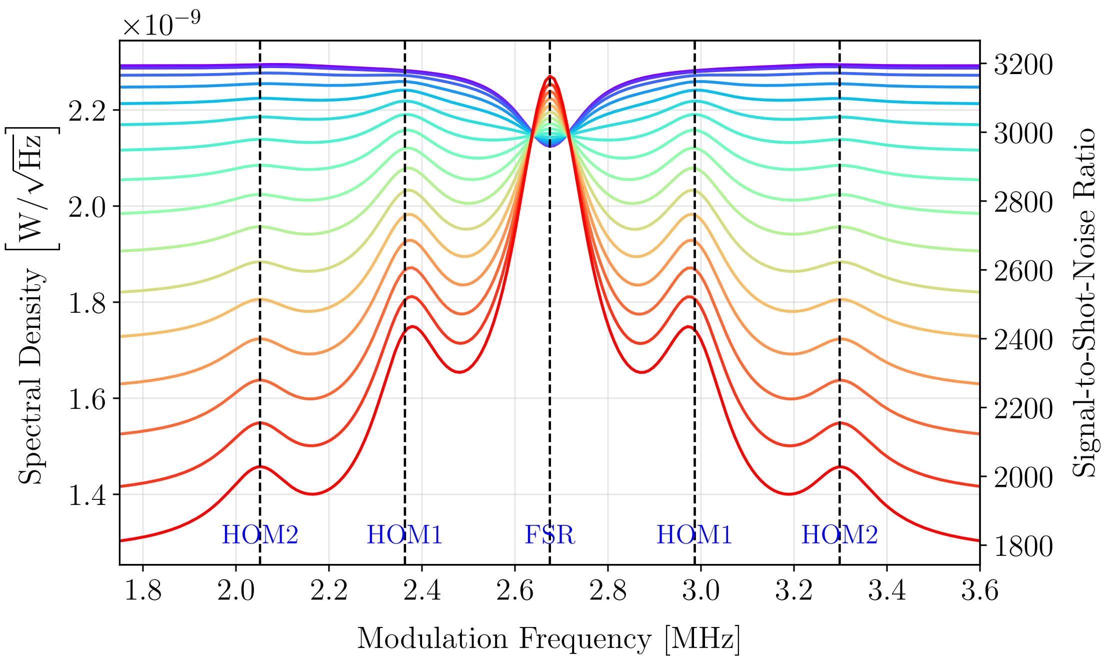

Figure 2: Expected SRC reflection of the amplitude-modulated SQZ laser at the ASC_AS_A RFPD. The curves correspond to an increasing angular misalignment of the SQZ beam injection axis into the SRC. The purple curve represents zero misalignment, which increases in 5 μrad increments up to 75 μrad (the red curve). Misalignment of the SQZ injection axis increasingly transfers power into HOMs, whose co-resonant sidebands appear as additional transmission resonances spaced at ~280 kHz intervals from the FSR. The exact spacing of these mode resonances is a direct measure of the SRC Gouy phase.