Noise-Stationary Locking and Phase-Controlled Dark-Port Injection

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Abstract- Interferometric sensors are commonly stabilized at a power fringe, resonance, or other convenient optical setpoint. Such lock points are useful for capture and drift control, but they do not necessarily minimize sensitivity of measurement noise to detuning jitter or auxiliary-field phase error. Noise-Stationary Locking (NSL) reframes the lock target as a stationarity condition on a measured noise objective. Phase-Controlled Dark-Port Injection (DPI) adds a controlled auxiliary field or quadrature resource through a nominally dark input and recovers a known phase signature through coherent or statistical correlation.

I. INTRODUCTION

For a Mach-Zehnder interferometer, optical cavity, mode cleaner, Sagnac loop, Michelson geometry, or integrated photonic interferometer, the selected operating point affects both signal gain and noise statistics. A conventional power lock may hold the apparatus near a transmission extremum or dark fringe, but a power extremum is not generally identical to a minimum-noise operating point.

NSL addresses this mismatch by regulating a setpoint to a local slope null of a noise objective rather than merely regulating optical power. DPI complements NSL by treating the nominally dark input as a controlled auxiliary channel whose phase waveform can be injected and recovered by correlation or synchronous detection.

II. DETECTION-NORMALIZED OBJECTIVE

Let *y(t;delta)* denote a detector output whose statistics depend on operating point *delta*. Over band $[f_1, f_2]$, a band-limited noise proxy is

$$N_{band}(delta) = integral_{f1}^{f2} S_y(f;delta)\, df. \quad (1)$$

$$V_{norm}(delta) = N_{band}(delta) / P(delta)^k,\ k >= 0. \quad (2)$$

The exponent k is selected according to the dominant noise regime. Shot-noise-like scaling suggests k near 1; power-squared technical noise suggests k near 2; detector-floor-dominated operation suggests k near 0.

y(t) → Nband → Vnorm → e(t)

Fig. 1. Noise-objective control path.

III. STATIONARITY AND JITTER COUPLING

$$V_{norm}(delta_0 + Delta\_delta) \sim= V_{norm}(delta_0) + (dV_{norm}/ddelta)|_{delta0}\, Delta\_delta + 1/2\, (d^2V_{norm}/ddelta^2)|_{delta0}\, Delta\_delta^2 + \ldots \quad (3)$$

When the controller drives the first derivative toward zero, the leading contribution from detuning jitter becomes second order. A small dither applied outside the protected measurement band allows synchronous demodulation to estimate the local slope and close the supervisory loop.

IV. DARK-PORT INJECTION AND QUADRATURE CONTROL

DPI applies a known phase waveform *g(t)* to an auxiliary field at a nominally dark input. In coherent detection the recovered signature can be linear in field amplitude; in direct or low-power detection it may appear as a second-order modulation of a noise-power statistic.

$$Var(X_{theta}) = V_{vac}[\, exp(-2r)cos^2(theta - g) + exp(+2r)sin^2(theta - g)\,]. \quad (4)$$

In squeezed-state variants, alignment near *theta = g* selects the reduced-noise quadrature. Optical loss and phase-angle jitter reduce the observable benefit, making a measured variance or information-related objective a natural supervisory target.

V. VALIDATION PATH

- *Noise-stationary lock test:* sweep delta, measure V_{norm}, identify a slope null, and compare against a power lock under injected jitter.
- *DPI recovery test:* apply a known *g(t)* waveform and recover it through coherent or noise-power correlation.
- *Quadrature test:* measure variance versus *theta - g* and verify phase-loop convergence.

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