

“Comparison and Status of Low-noise X-band Oscillator and Amplifier Technologies”

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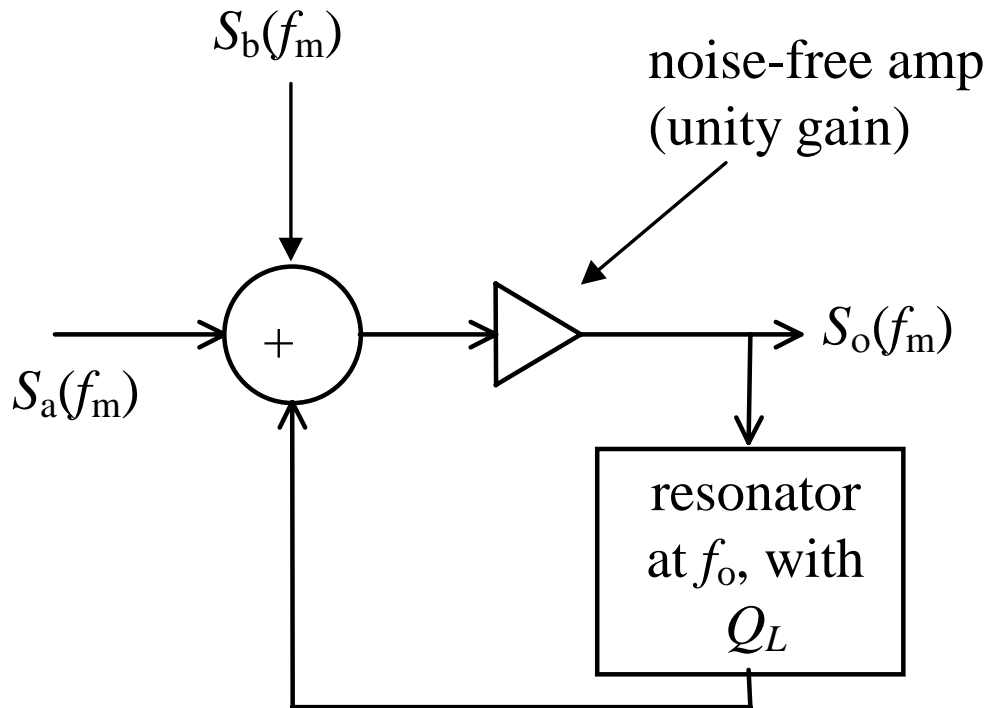
Collaborations with Army Research Lab, Office of Naval Research, Optical Frequency Measurements and Ion Storage (NIST), Mayo Foundation, MIT-LL

Acknowledgements of OEWaves, Inc., Poseidon Scientific, Q-Dot, Corp.

OUTLINE OF TALK

- **Best-in-class PM noise results and descriptions of X-band amplifiers and oscillators based on recent measurements at NIST. Results are at an operating frequency of 10 GHz.**
- **Amplifier PM-noise measurements of:**
 - SiGe with feedback noise suppression (FBA)
 - Commercial amplifiers with feedforward noise suppression (FFA)
 - Array of commercial amplifiers with uncorrelated noise
 - Typical commercially available amplifiers
- **Impact of amplifier feedback noise on oscillator, review of Leeson's model**
- **Oscillator PM-noise measurements of:**
 - Typical low-noise quartz oscillator, multiplied to 10 GHz
 - Optical Electronic Oscillator using fiber-delay-line resonator
 - Sapphire-loaded CSO using interferometric carrier suppression
 - High-power air-dielectric CSO using 2W drive and impedance controlled carrier suppression
 - DRO feedback oscillator
 - Optical femtosecond-comb divider with calcium-stabilized reference oscillator

Origins of oscillator phase noise motivates low-noise amplifier development



Phase stabilization of an oscillator with noise sources and a resonator with loaded Q , Q_L .

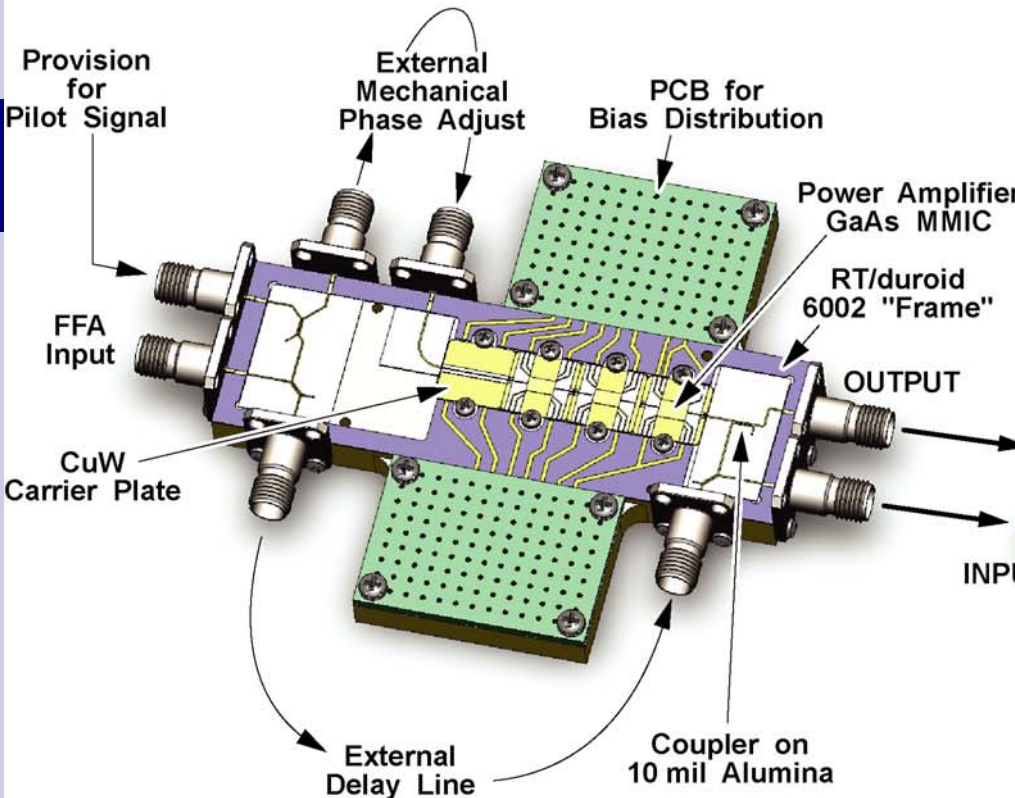
Low-noise Microwave Amplifier Measurements

GENERAL STRATEGY TO ACHIEVE LOW RESIDUAL PHASE NOISE IN AMPLIFIERS

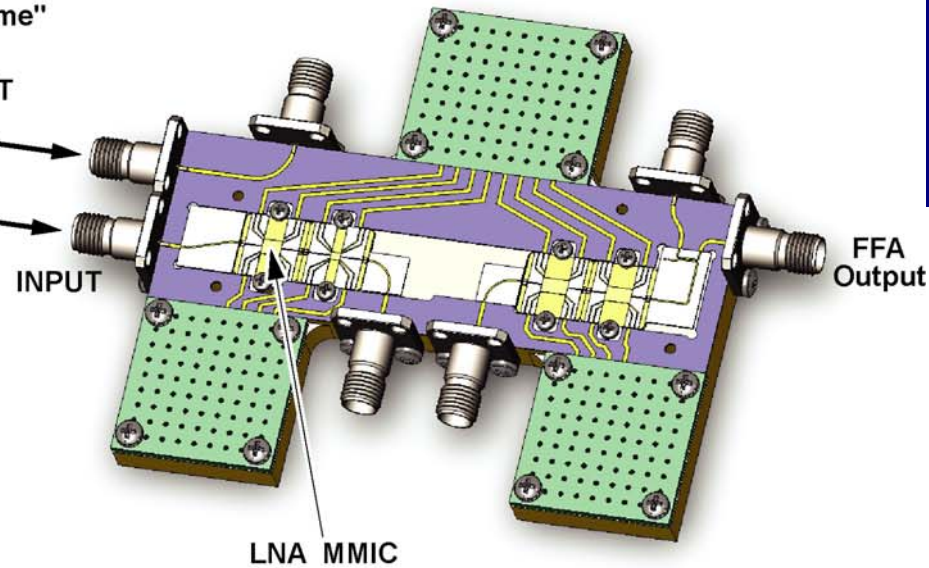
- Use low $1/f$ noise devices
 - $1/f$ noise multiplies up into near carrier noise due to amplifier non-linearities
 - Generally HBTs have smaller low-frequency noise than all classes of FETs
- Use a design technique that achieves highly linear amplifier operation
Possibilities include:
 - Feedback (requires high f_t)
 - Feedforward (best over a narrow band with careful phase match)
 - Parallel HBTs that are graded for low $1/f$ noise (power/size cost)
 - Predistortion (adds to device noise)
 - LINC -linear amplification using non-linear components (sampling-rate limited)

**MECHANICAL DRAWINGS OF FIRST AND SECOND LOOP MODULES
OF HYBRID FEEDFORWARD AMPLIFIER (FFA)
(Each Module Plan Dimensions: ~4" x 3")**

LOOP 1 MODULE



LOOP 2 MODULE

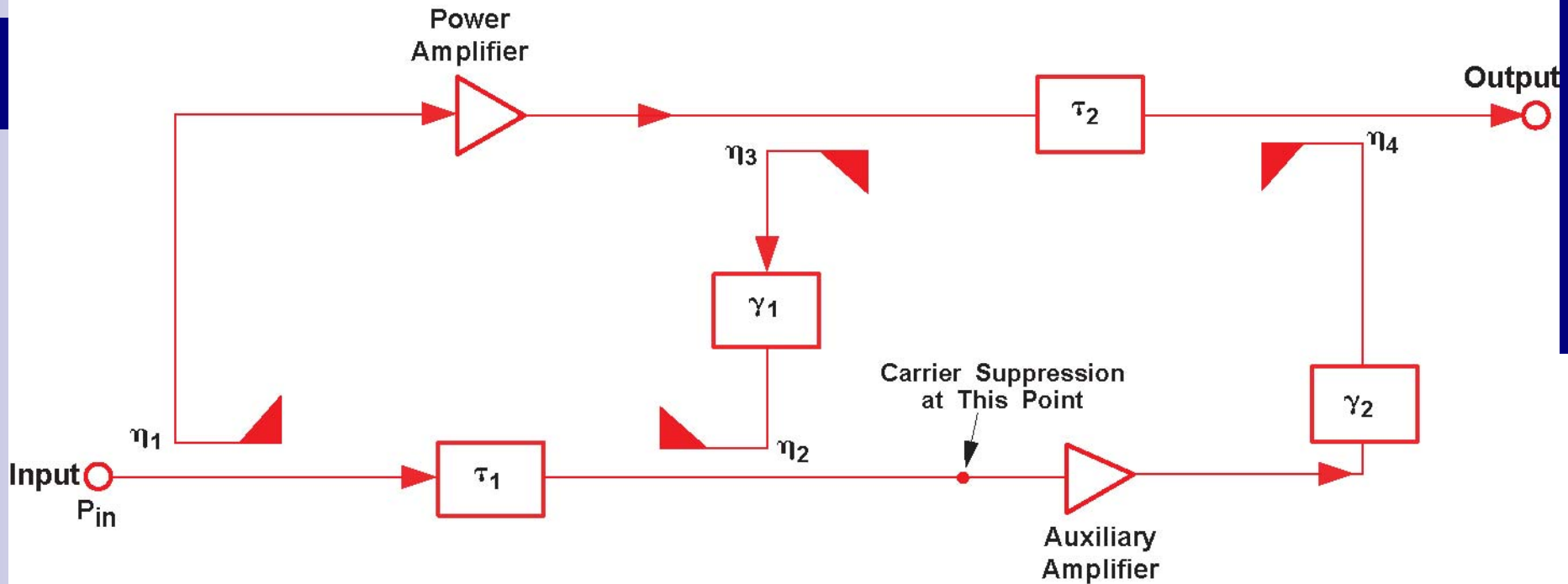


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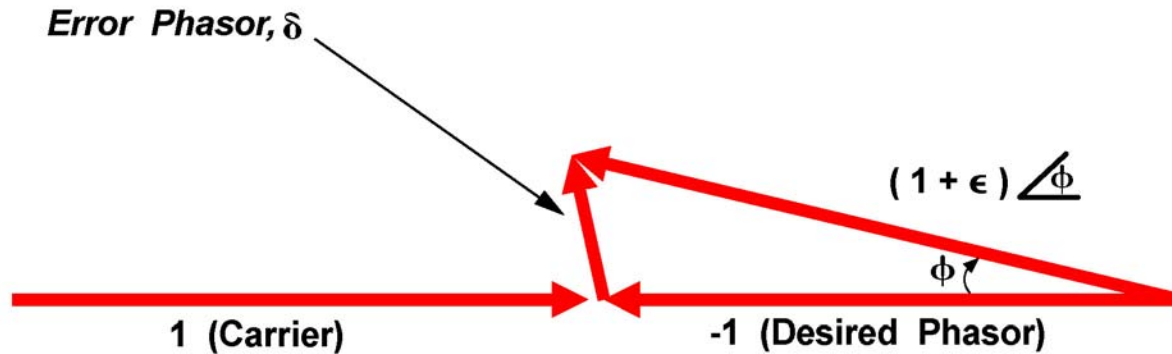
Low-noise Microwave Amplifier Measurements

BLOCK DIAGRAM FOR BASIC FEEDFORWARD AMPLIFIER



MAY_12 / 2003 / VS / 19057

PHASOR DIAGRAM REPRESENTING IMPERFECT CARRIER SUPPRESSION



$$|\delta|^2 = 1 + (1 + \epsilon)^2 - 2(1)(1 + \epsilon) \cos(\phi)$$

Phase Mismatch = ϕ

Amplitude Mismatch_(dB) = $10 \log(1 + \epsilon)^2$

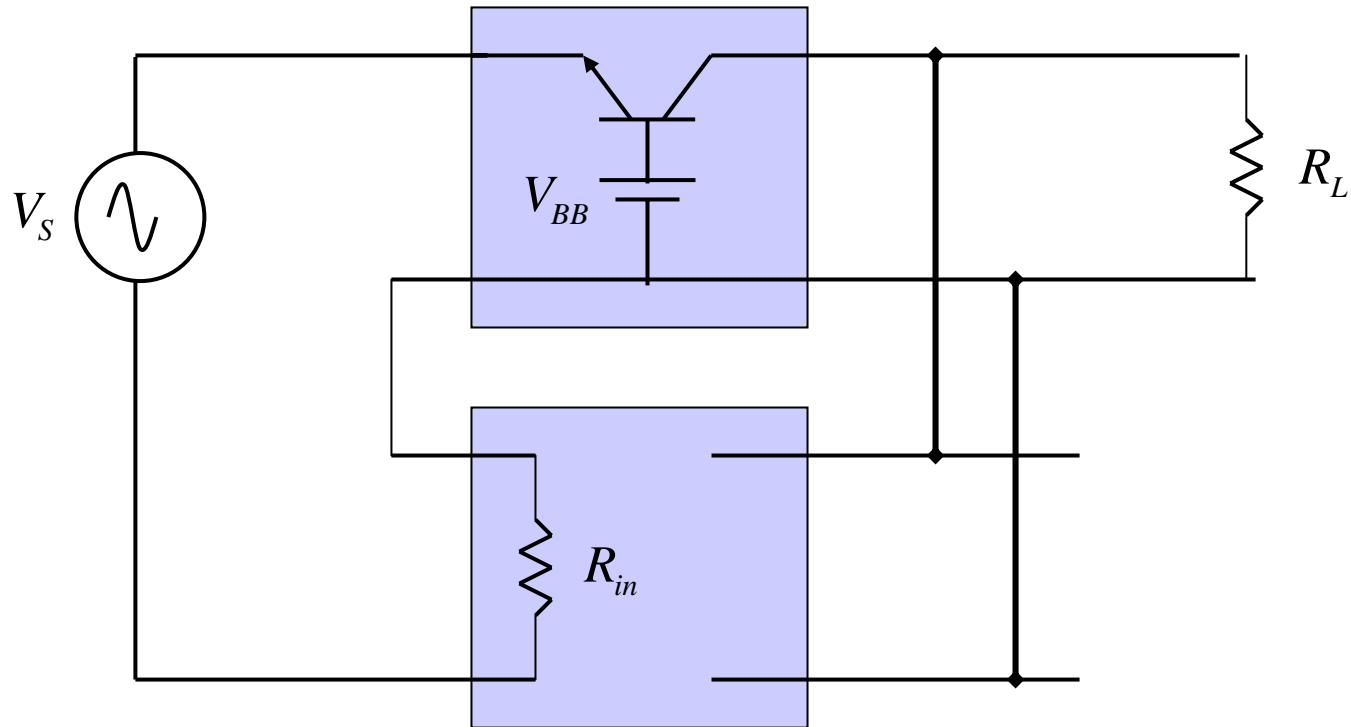
Carrier Suppression Factor, CS_(dB) = $10 \log|\delta|^2$



MAY_13 / 2003 / VS / 19059

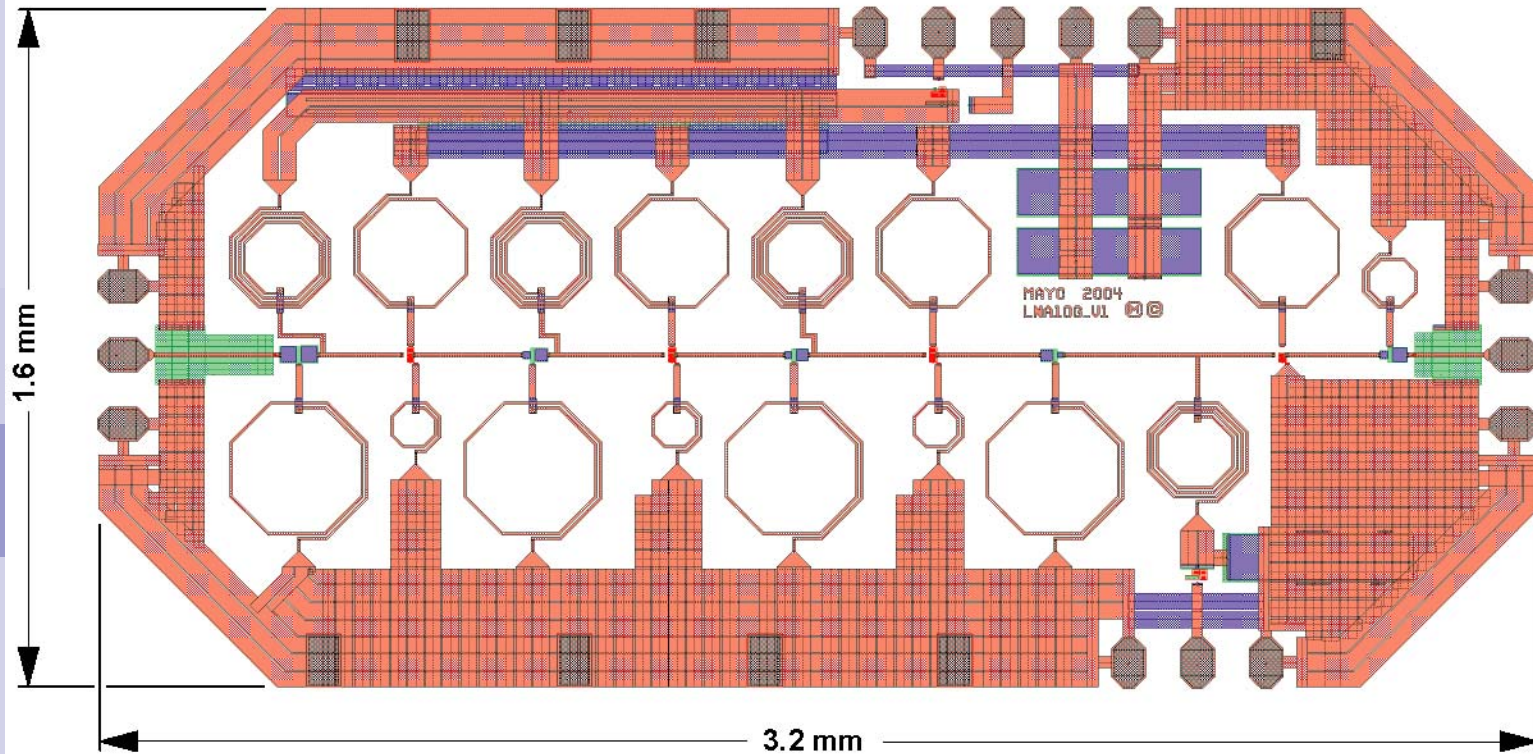
Feedback in Common-Base Amplifier

- f_t of 350 GHz attained in SiGe HBT



- Series-shunt feedback configuration

FOUR STAGE 10 GHz LNA USING JAZZ 0.18 μm SiGe TECHNOLOGY
 (Evaluation Will Be Done to Investigate 1/f Noise of SiGe HBT LNA's;
 Simulated Noise Figure = 2.7 dB with Associated Gain of 26 dB)

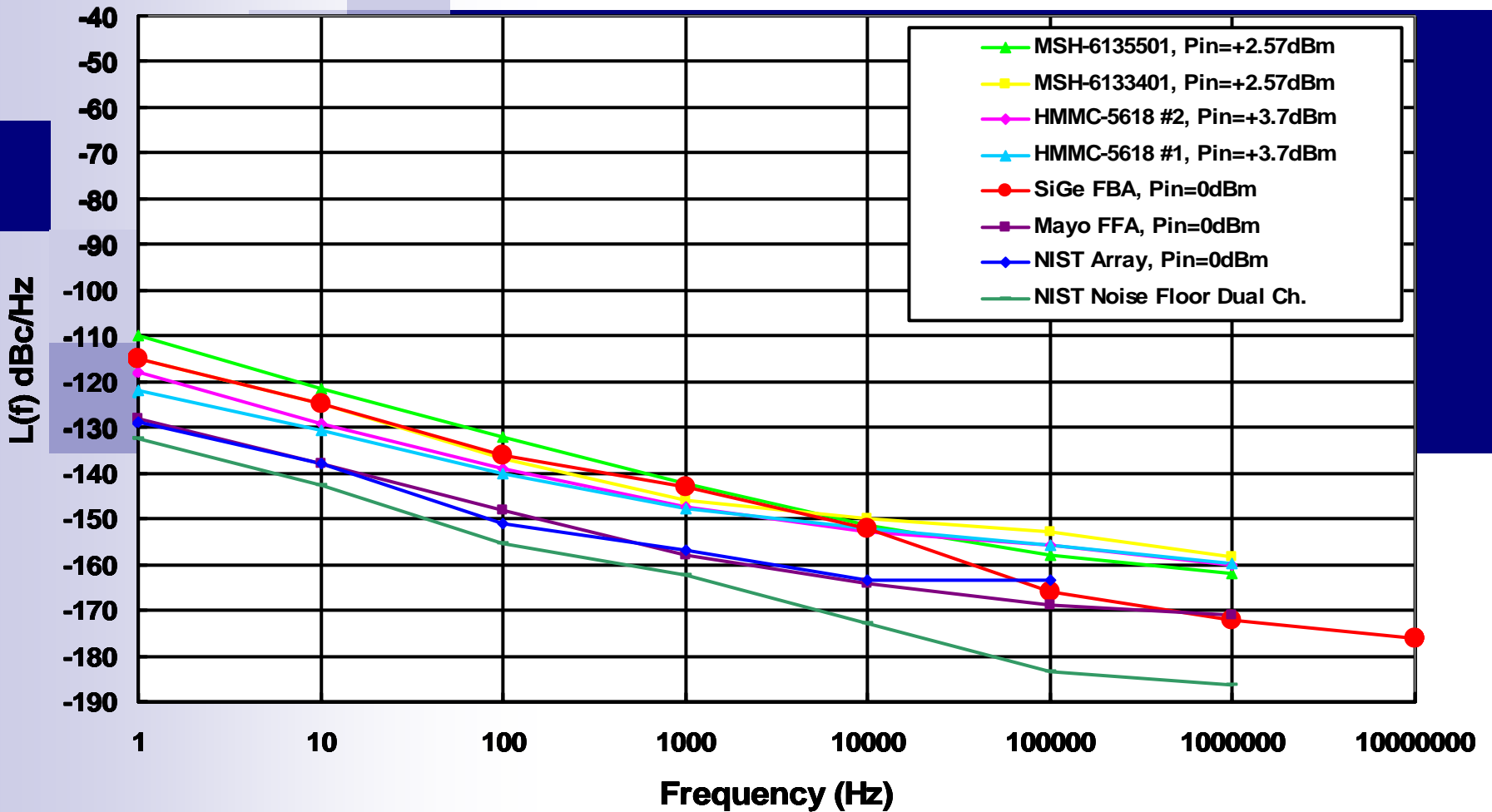


JAN_16 / 2004 / RAK / 19706



Courtesy of Mayo Foundation

10 GHz Low-noise Microwave Amplifier Measurements

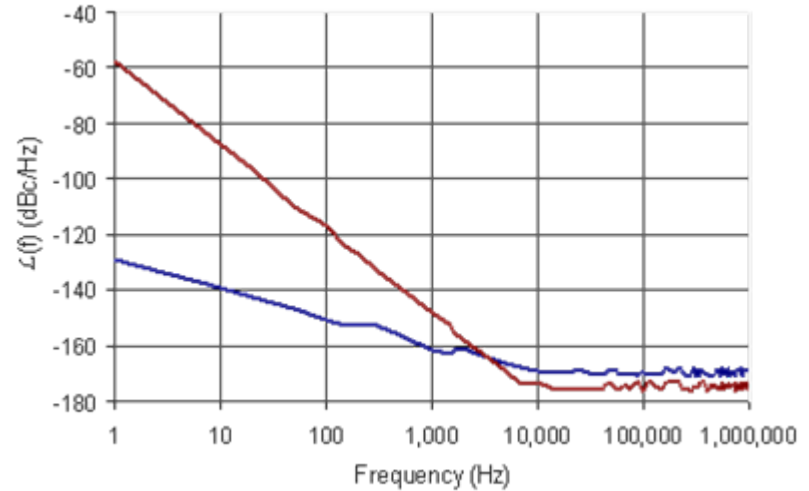


Leeson's Oscillator Noise Model

$$S_{\phi}^{OSC}(f) = \begin{cases} \frac{\nu_o^2 S_{\phi}(f)}{4Q^2 f^2} & f < \frac{\nu_o}{2Q} \\ S_{\phi}(f) & f > \frac{\nu_o}{2Q} \end{cases}$$

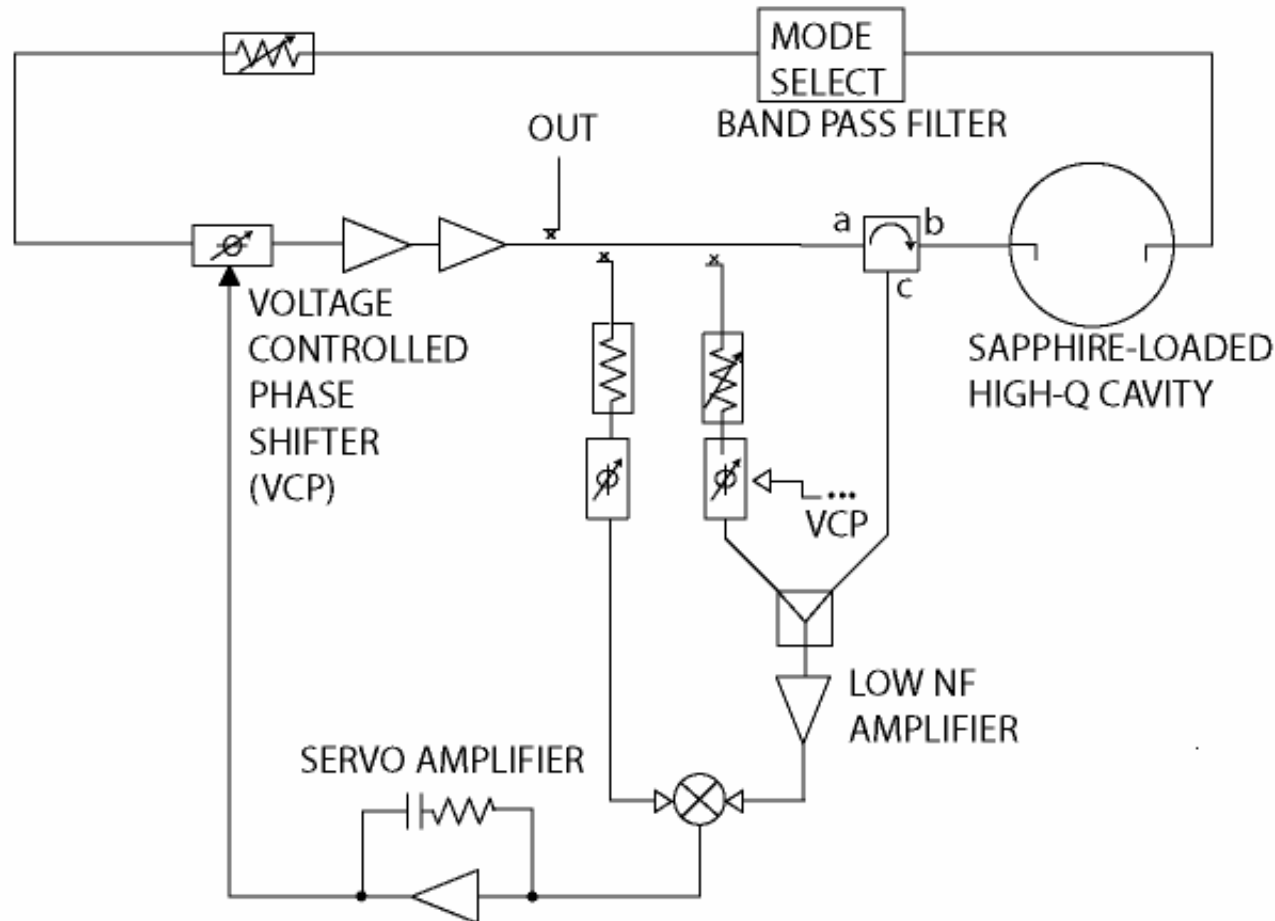
$$f = \nu - \nu_o$$

Fourier frequency (offset frequency)



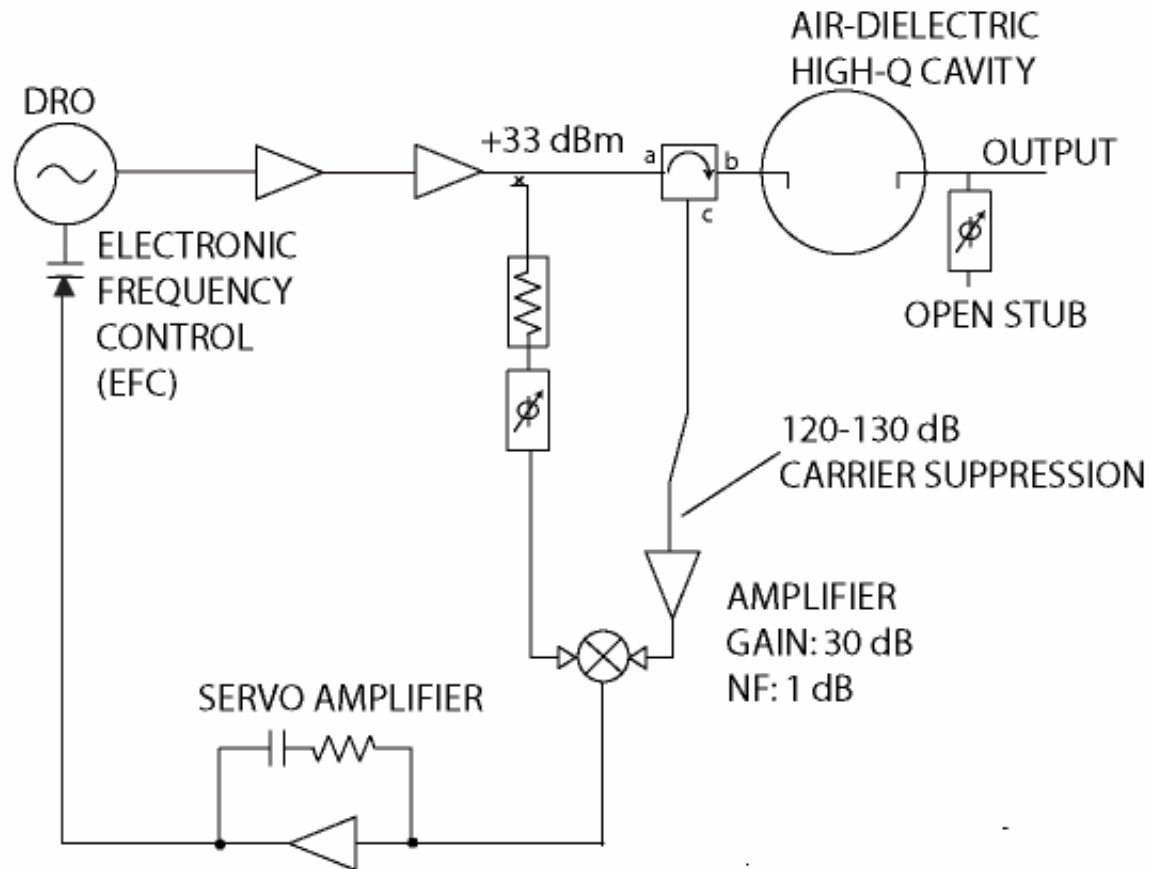
D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE Lett.*, 1966.

SLCO Interferometric Stabilized Cavity Loop Oscillator



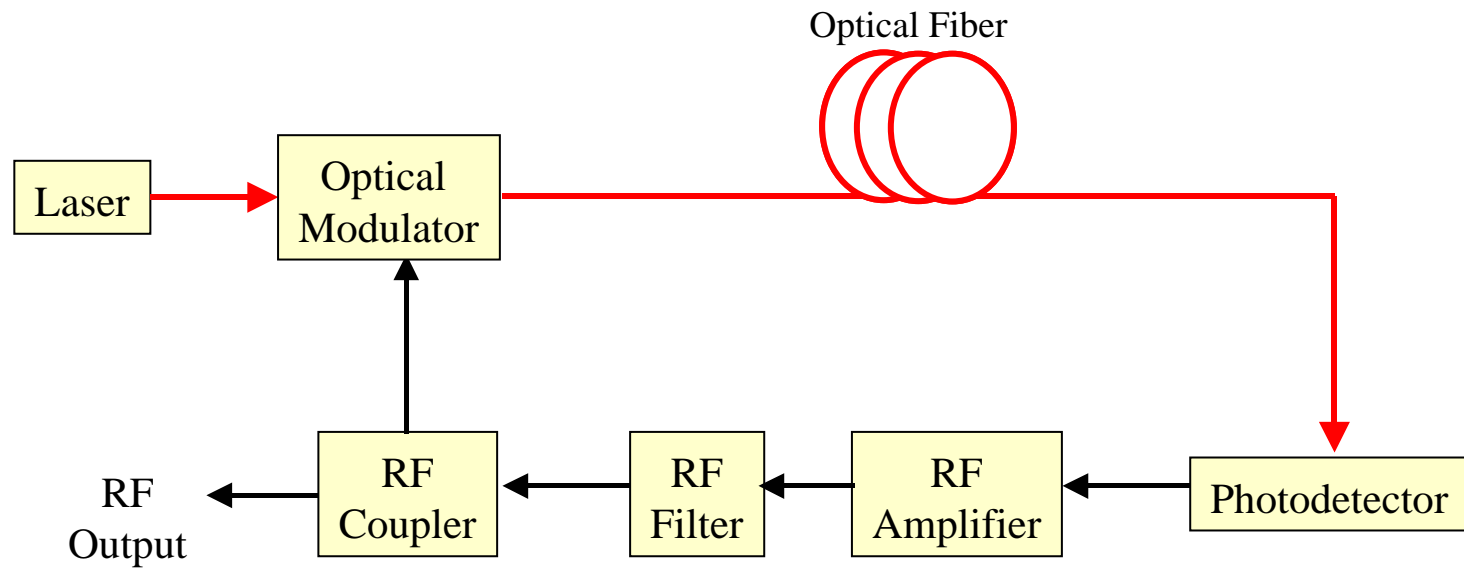
Feedback oscillator in which the high-Q cavity serves both as the resonator and the discriminator. **Carrier suppression** and **high Q** increase discriminator sensitivity.

Impedance-controlled-coupling, Cavity-stabilized DRO/YIG



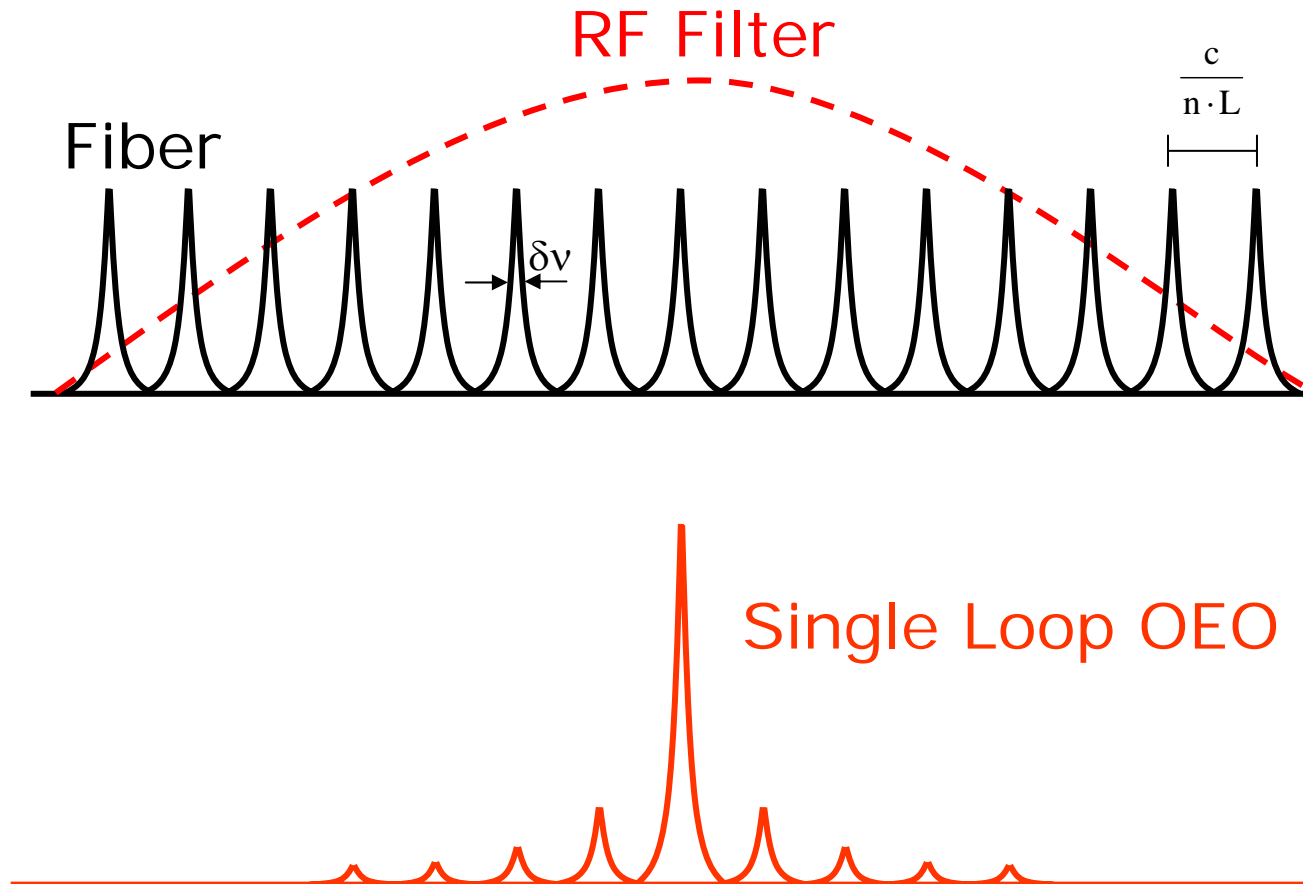
Cavity stabilization of a DRO or YIG oscillator. Cavity serves as passive discriminator. **Carrier suppression** and **high drive power** increase discriminator sensitivity.

Single-fiber Opto Electronic Oscillator (OEO)



Courtesy of OE Waves, Inc.

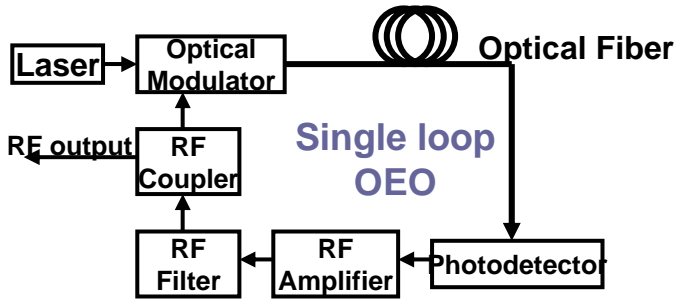
Single-fiber Opto Electronic Oscillator (OEO)



Courtesy of OEWaves, Inc.

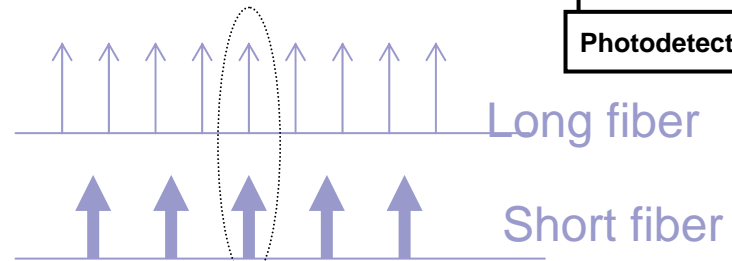
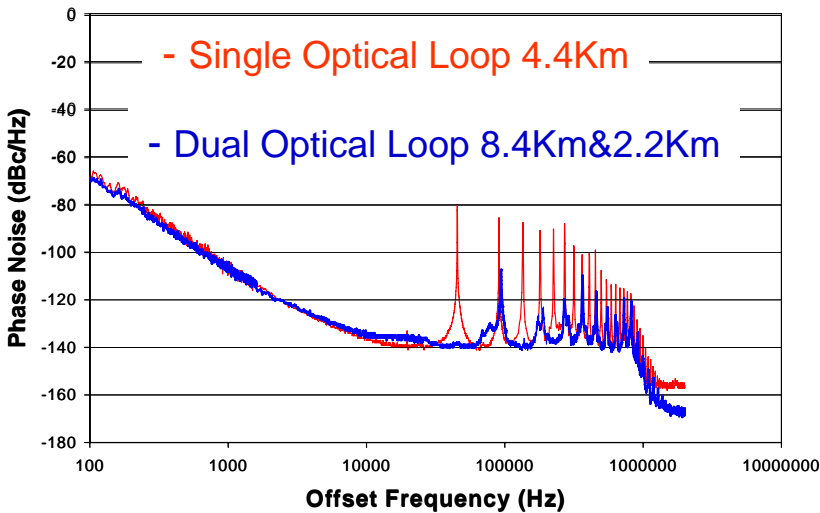
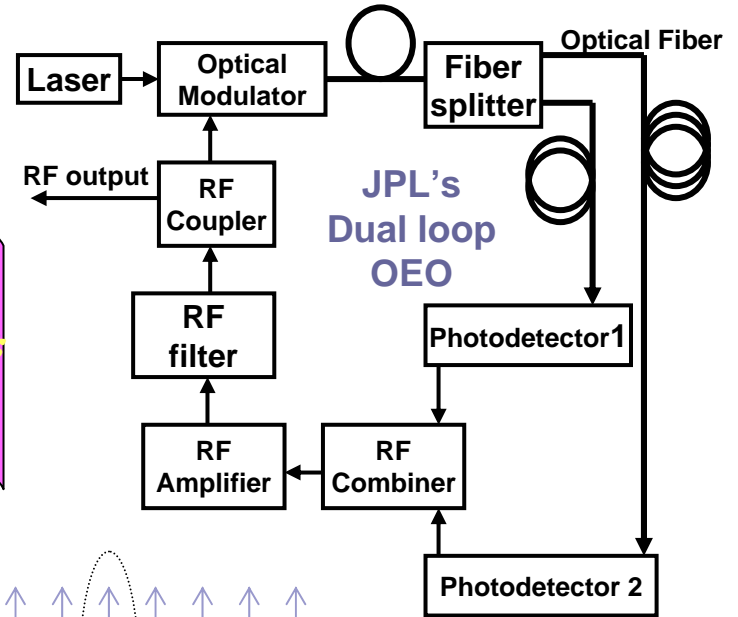
Opto-Electronic Oscillator

- OEO has very high Q and frequency agility over a wide range...



*Q = 10¹¹ in optical systems
And Low g-sensitivity*

- But long fiber OEO has spurs...

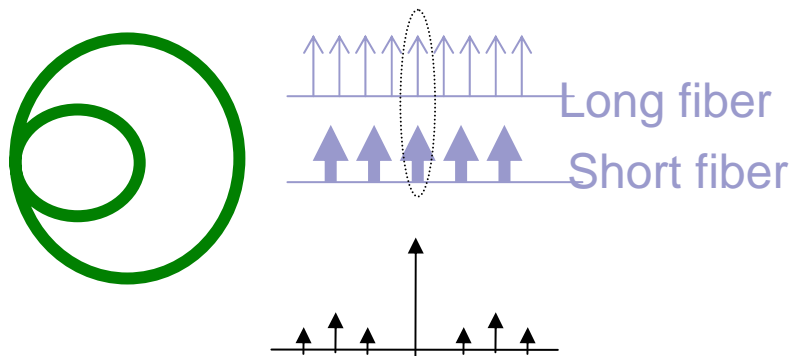


Multi-loop OEO reduces spurs, but:

- Not enough spurious suppression for many RF system needs.
- Worse phase noise performance.

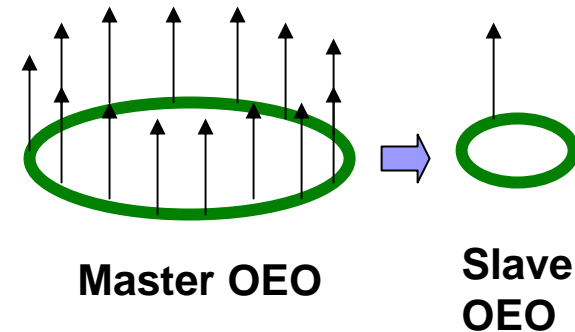
Comparison

- The Multi-loop OEO uses “energy competition” between carrier mode and spur modes to suppress spurs.



Spurs are suppressed.

- For the Injection-Locked OEO: *the spurs from the master OEO cannot be supported by the slave OEO's.*



In principle, spurs can be “eliminated” by destructive interference.

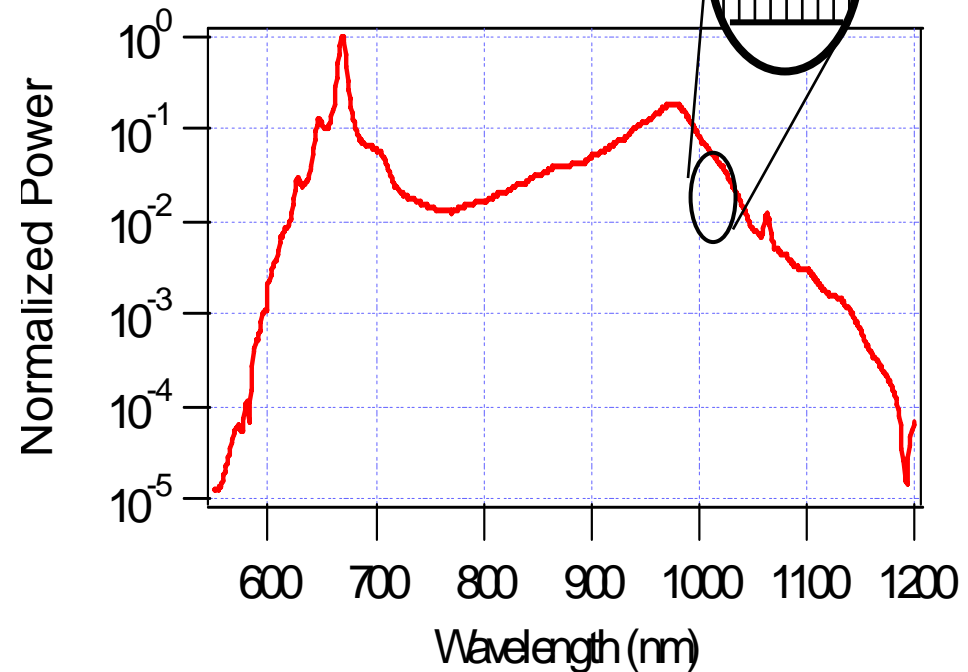
Broadband Femtosecond Mode-locked Laser Comb

Femtosecond Comb Optical Divider f_r



Femtosecond Ti:Sapphire laser, the heart of the femtosecond laser frequency comb

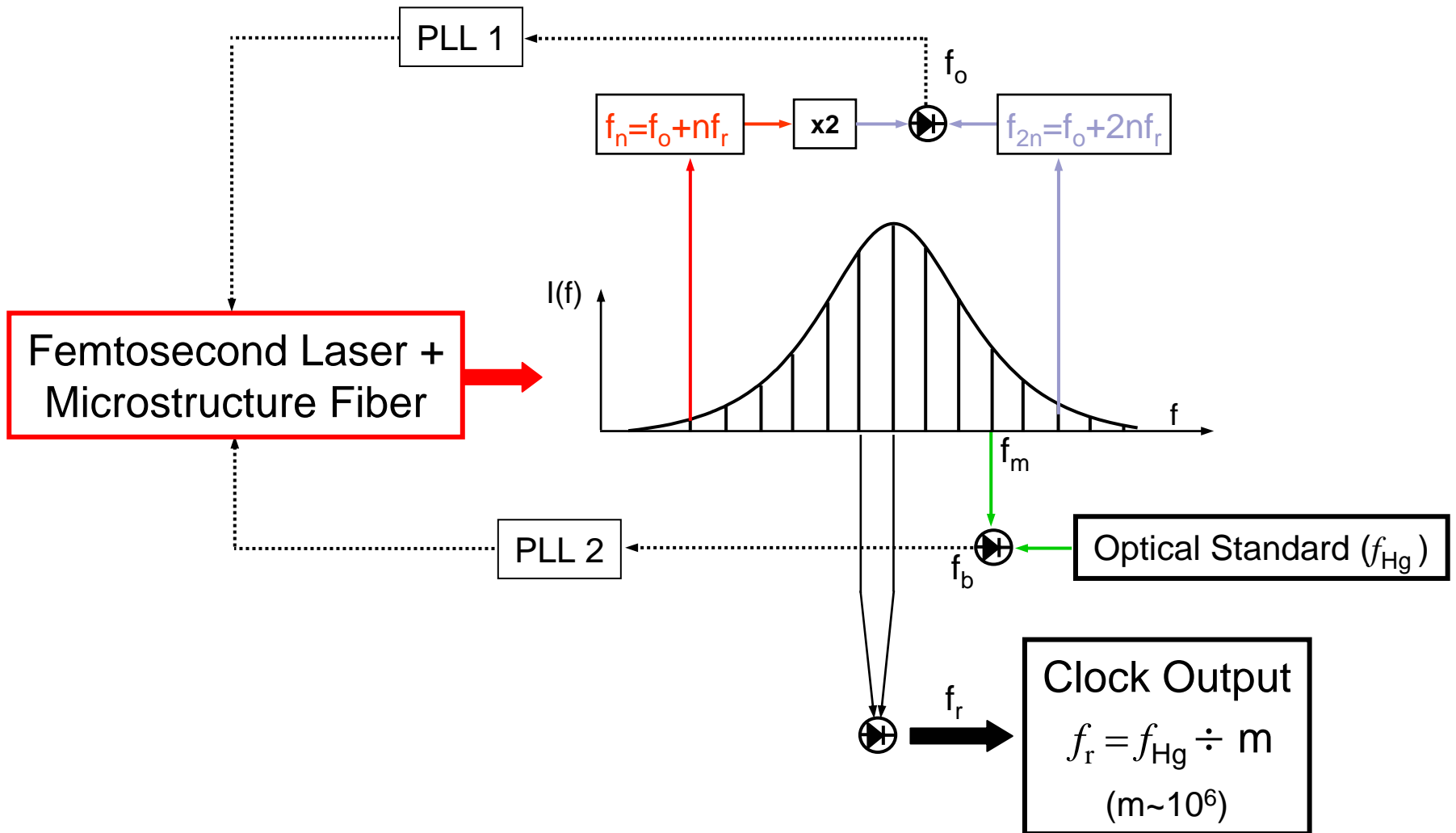
- Broadband femtosecond lasers require more careful control of the intracavity dispersion and laser alignment.
- In this particular case, the convex mirror provides enhanced self-amplitude modulation which generates shorter pulses and broader spectra



A. Bartels and H. Kurz, *Opt. Lett.* **27**, 1839 (2002)

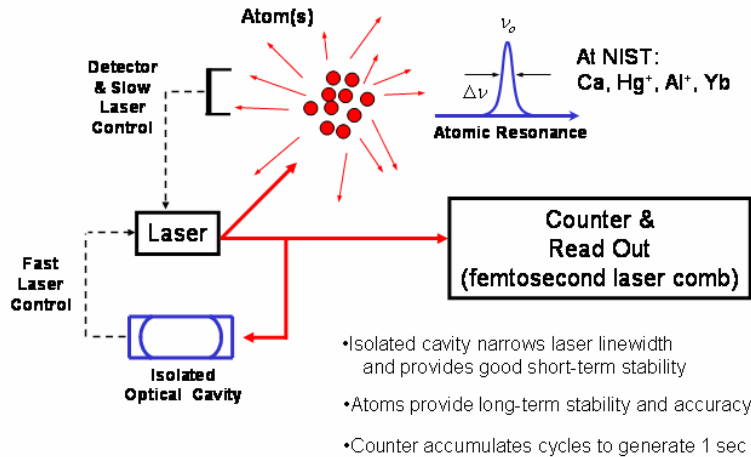
Dividing Down: Controlling f_r with an Optical Reference

Femtosecond Comb Optical Divider

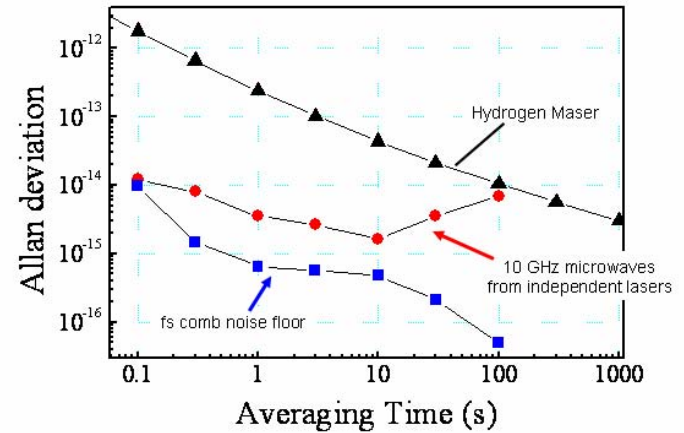


Ultra-low PM Noise from Optical Sources

The Components of an Optical Clock



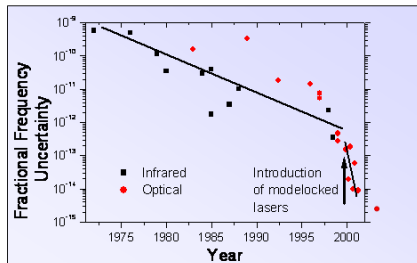
Stable Microwaves from Optical Oscillators



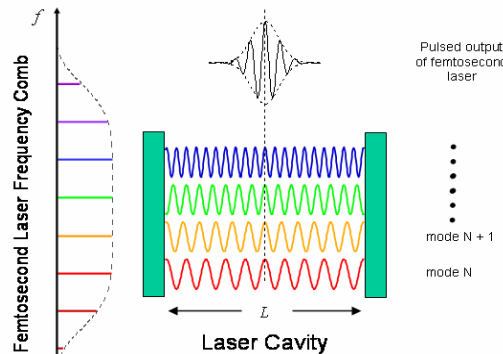
Optical sources now generate some of the most stable microwaves

Impact of femtosecond lasers on frequency metrology

- Femtosecond laser frequency combs have dramatically
 - Decreased uncertainty
 - Simplified measurements



The femtosecond mode-locked laser comb

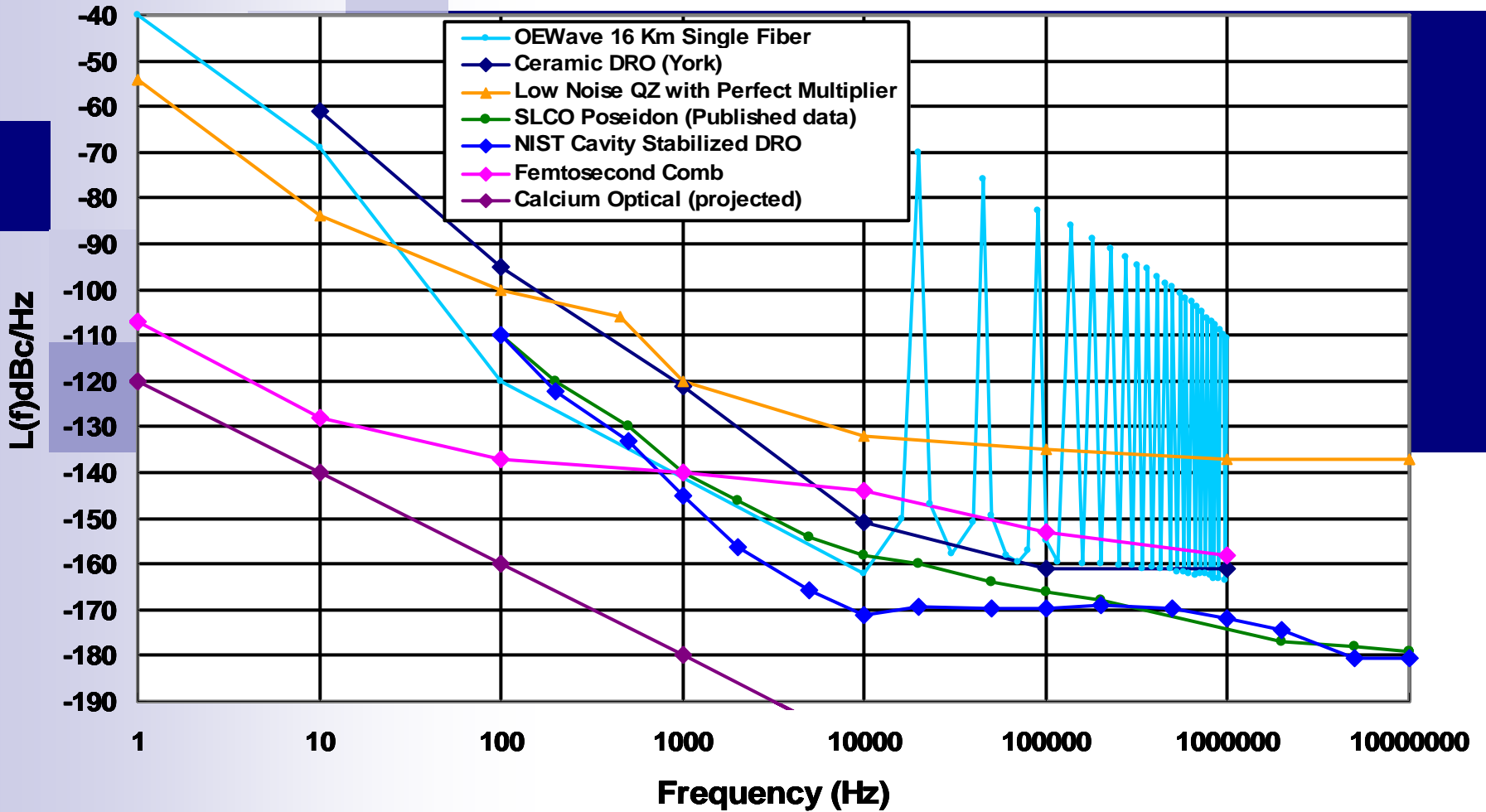


→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/c$.

Femtosecond Lasers Provide...

- Convenient "gears" for optical clocks and a means for comparing clocks
- Linking to virtually all frequency domains (RF – optical)
 - Generation of low noise signals across the optical and microwave domains.
- A new tool for laser spectroscopy
- An opening to new applications and techniques
 - **Absolute** femtosecond timing capabilities
 - Secure communications
 - Advanced navigation, sensors, radar, etc.
 - Fundamental physics
 - Ultrafast science

10 GHz Low-noise Microwave Oscillator Measurements



The End

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Thanks to many contributors.

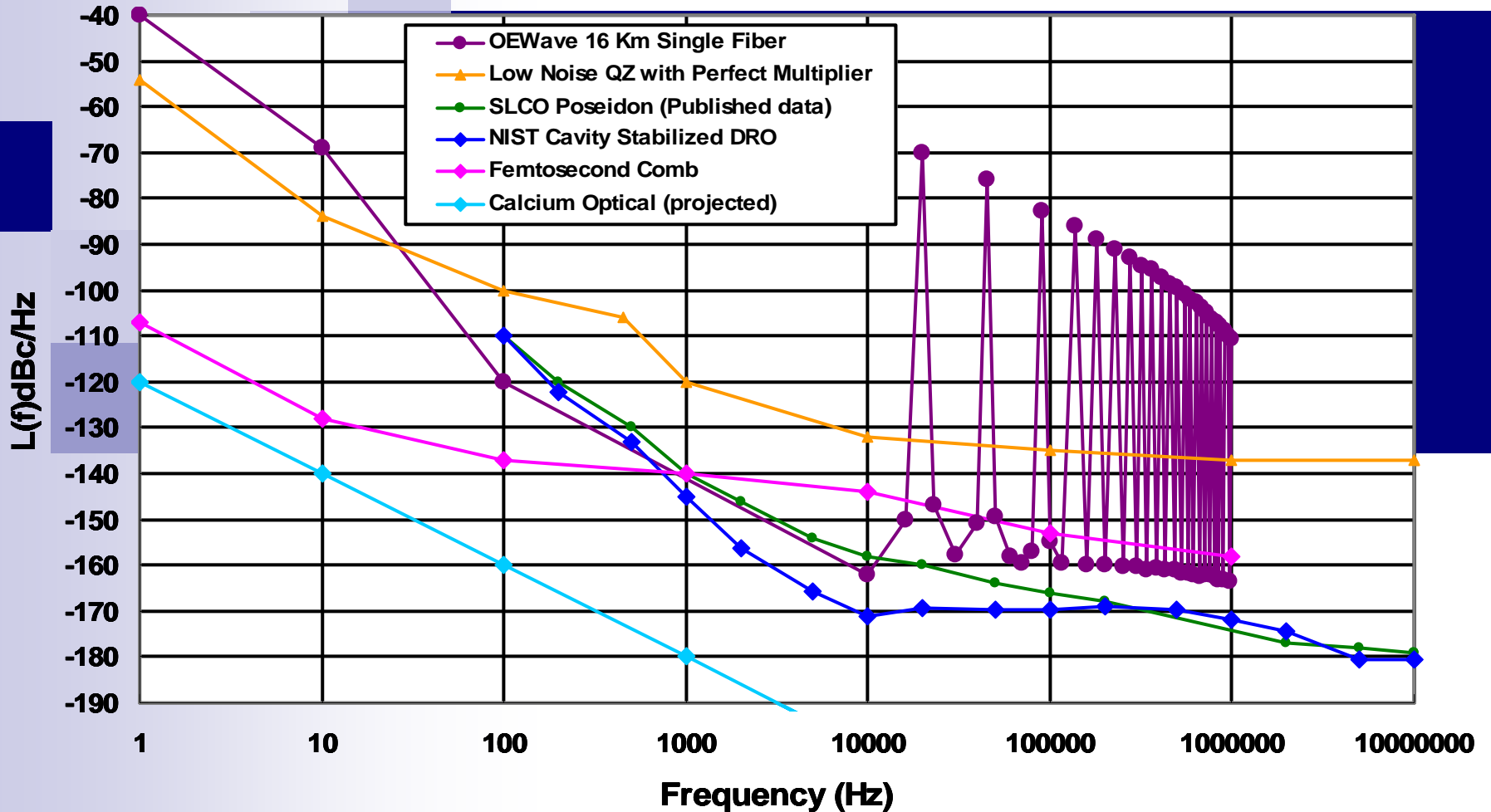
Conclusion

- **Comparison of different classes of microwave amplifiers and oscillators at X-band**
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- H. Ainspan, M. Soyuer, J. O. Plouchart, J. Burghartz, “A 6.25 GHz Low DC Power Low-Noise Amplifier in SiGe”, IEEE Custom Integrated Circuits Conference, 1997.
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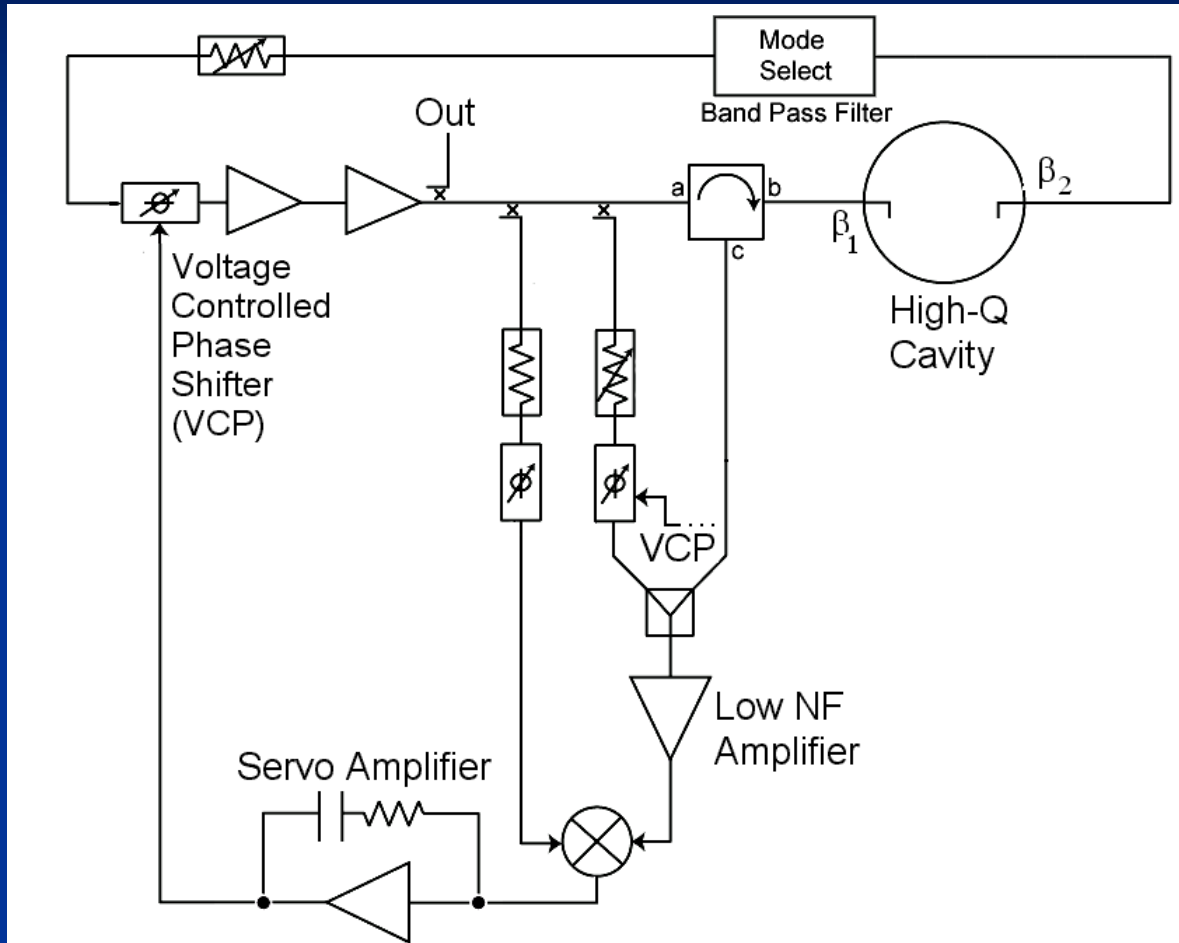
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Low-noise Microwave Oscillator Measurements

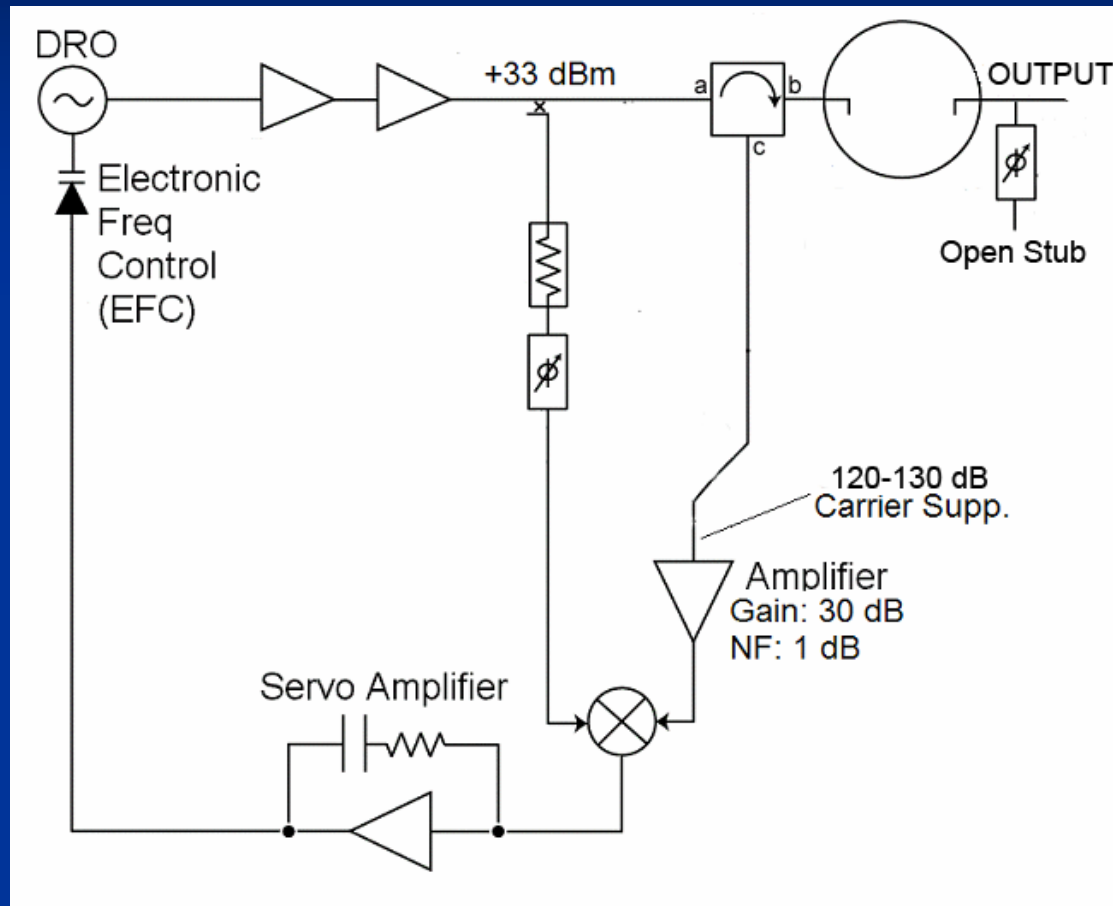


SLCO Interferometric Stabilized Cavity Loop Oscillator



Active oscillator in which the high-Q cavity serves both as the resonator and the discriminator. **Carrier suppression** and **high Q** increase discriminator sensitivity.

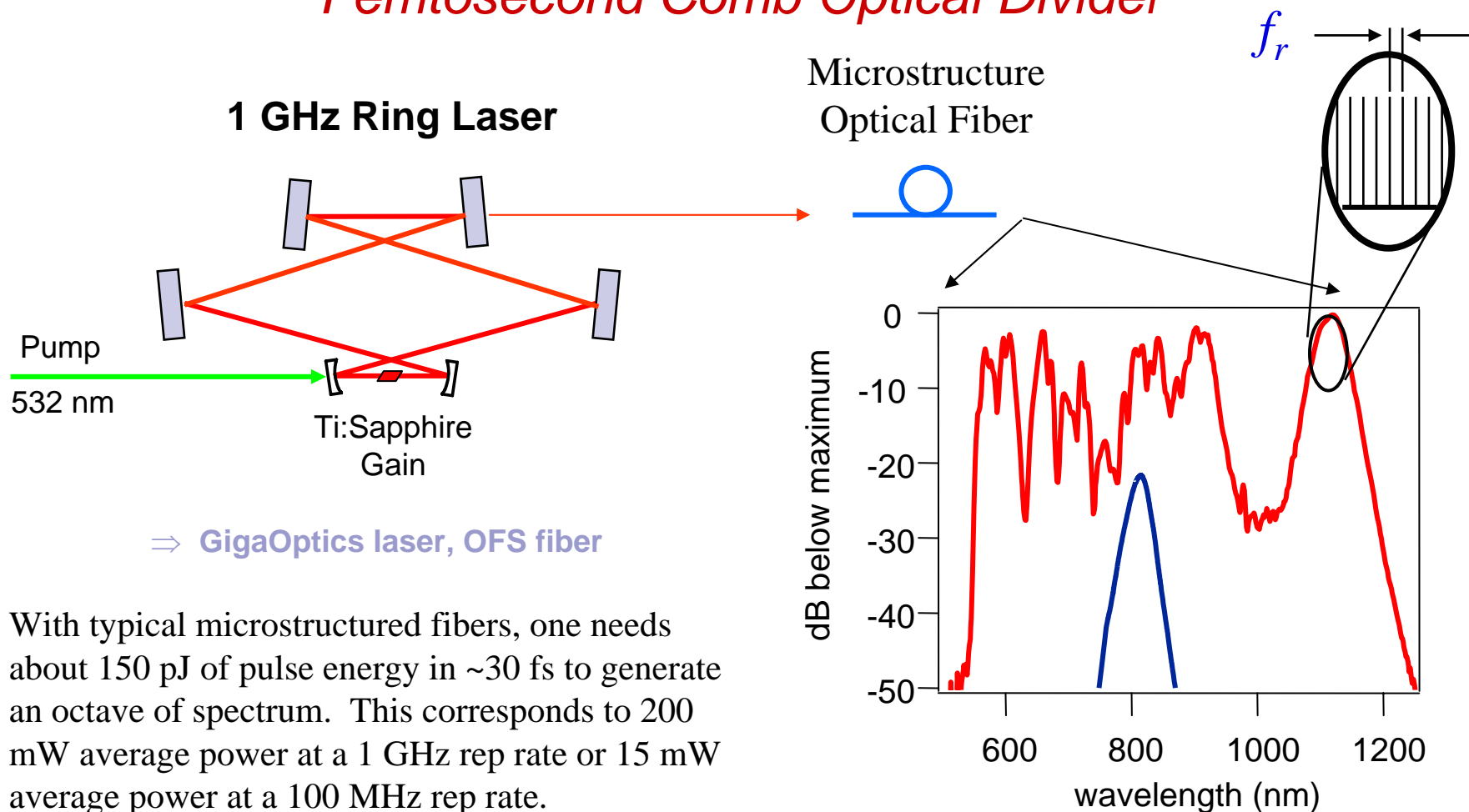
Impedance-controlled-coupling, Cavity-stabilized DRO/YIG



Cavity stabilization of a DRO or YIG oscillator. Cavity serves as passive discriminator. **Carrier suppression** and **high drive power** increase discriminator sensitivity.

An Octave-Spanning Comb using Microstructure Fiber

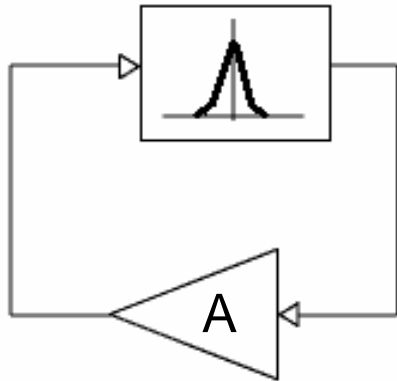
Femtosecond Comb Optical Divider



With typical microstructured fibers, one needs about 150 pJ of pulse energy in ~30 fs to generate an octave of spectrum. This corresponds to 200 mW average power at a 1 GHz rep rate or 15 mW average power at a 100 MHz rep rate.

Oscillators' noise

$$H \approx H_0 e^{-j \frac{2fQ}{\nu_0}}$$



$$A = A_0 e^{j\phi}$$

$$S_{\phi}^{OSC}(f) = \begin{cases} \frac{\nu_o^2 S_{\phi}(f)}{4Q^2 f^2} & f < \frac{\nu_o}{2Q} \\ S_{\phi}(f) & f > \frac{\nu_o}{2Q} \end{cases}$$

Leeson's model*

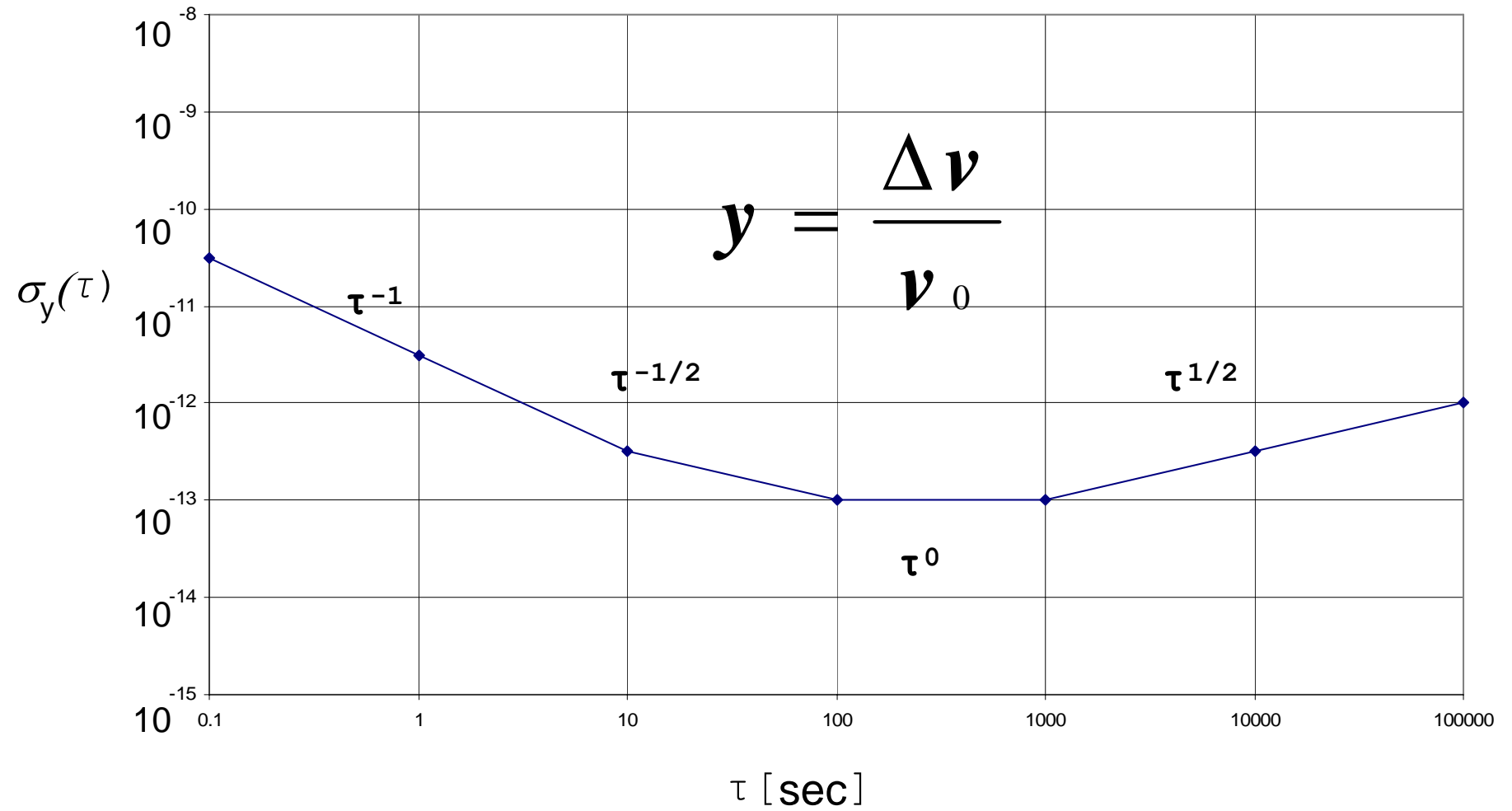
oscillation condition:

$$f = \nu - \nu_o$$

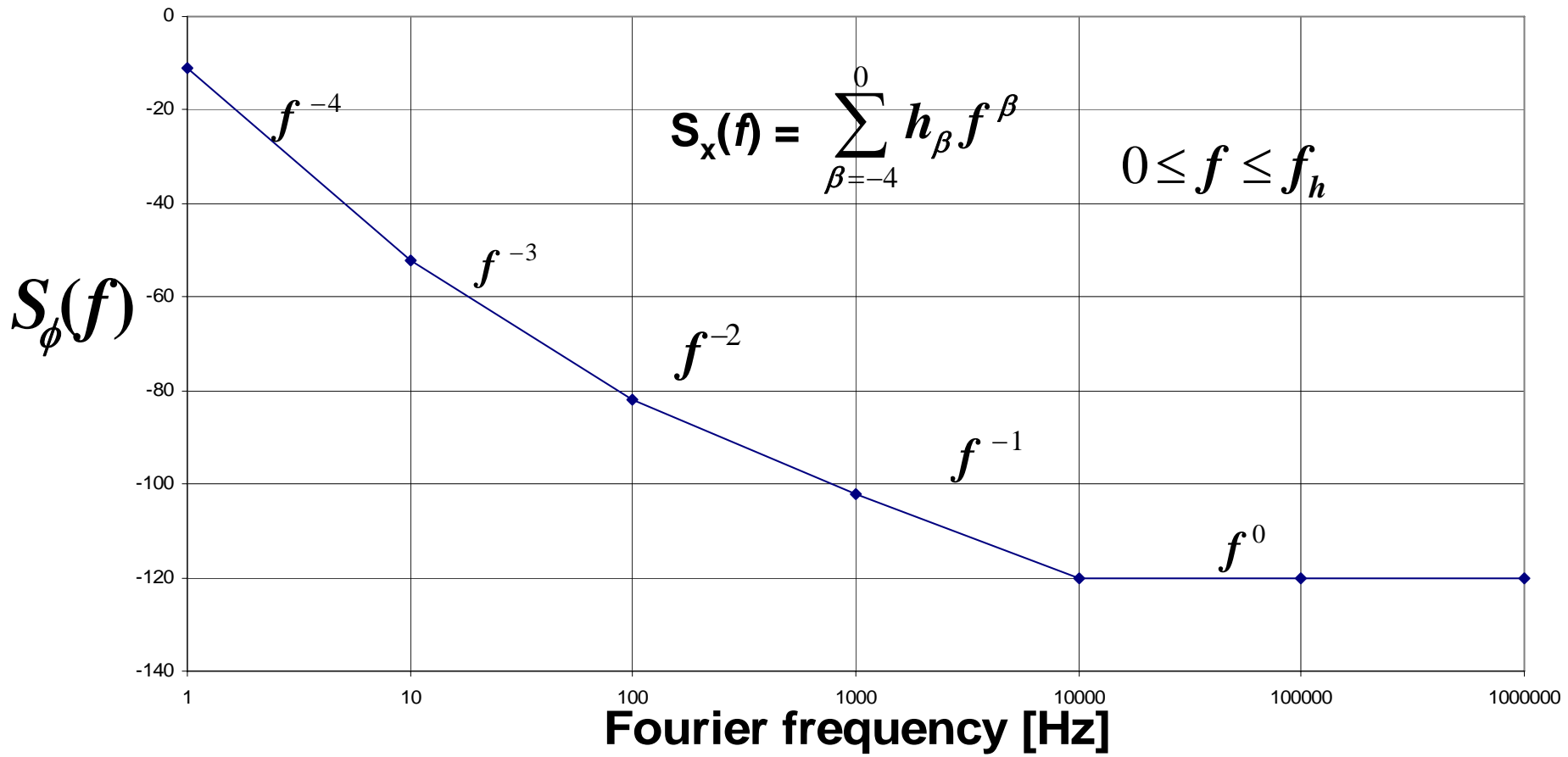
$$A g H = 1$$

Fourier frequency (offset frequency)

*D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE Lett.*, 1966.



New calculation



Frequency Domain
Power Spectral Density
of phase fluctuations

$\beta = \alpha - 2$	Noise type	$\sigma_y(\tau)$
0	White phase	$\propto \tau^{-1}$
1	Flicker phase	$\propto \tau^{-1}$
2	Random walk phase	$\propto \tau^{-1/2}$
3	Flicker frequency	$\propto \tau^1$
4	Random walk frequency	$\propto \tau^0$

Allan Deviation of
fractional frequency fluctuations
Time Domain

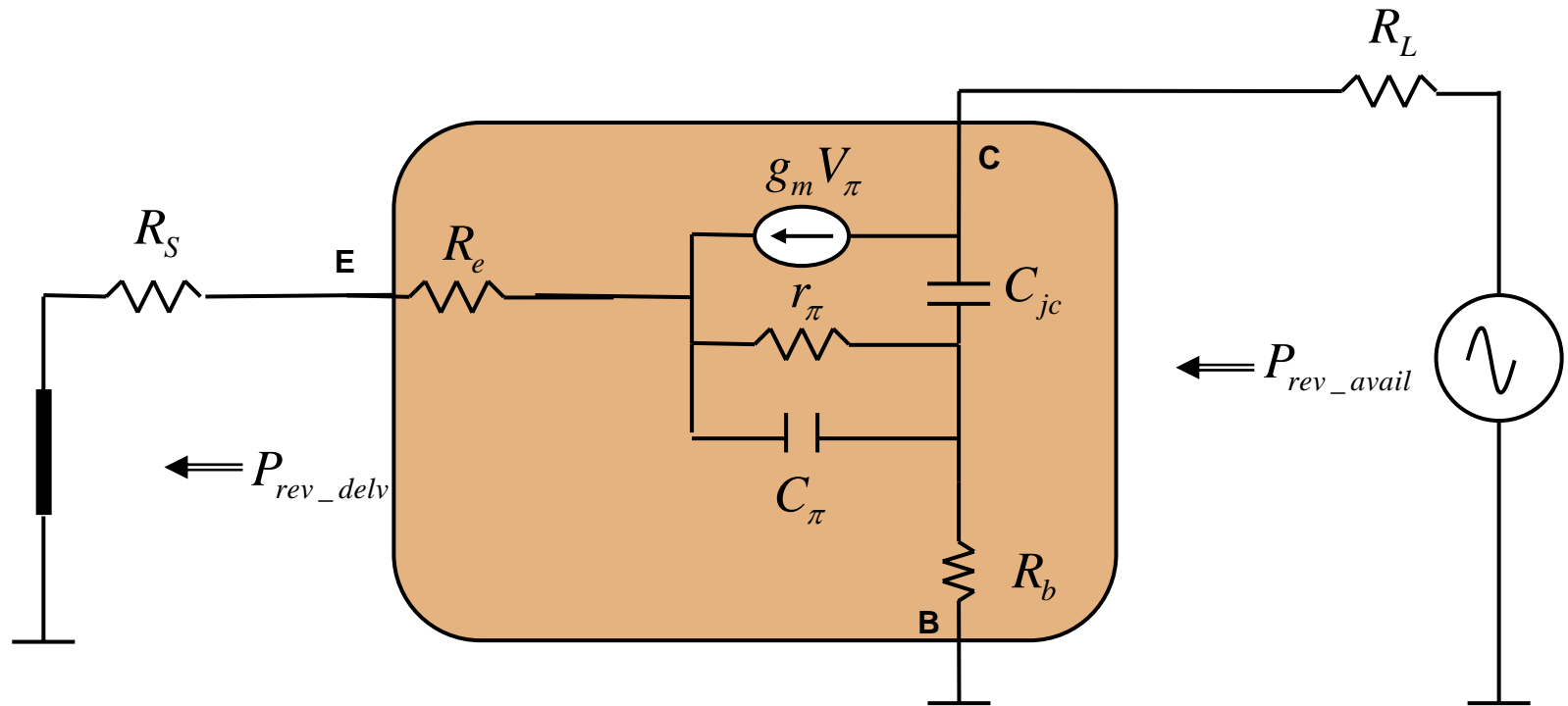
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C-B LNA: Reverse Isolation



- Examining the circuit it is clear that virtually none of the signal at the output port appears at the input port. C-B amplifier therefore offers excellent reverse isolation.

IV. LEESON'S EQUATION

1. Origins of Phase Noise

A simple feedback loop (phase servo) predicts phase noise from device noise figure, baseband noise sources and resonator Q .

2. Leeson's Equation

Predicts Spectral Density (PSD) of Phase Fluctuations from $1/f$ noise, noise figure, carrier power and loaded Q .

$S_a(f_m)$: Additive white thermal noise power at f_o .

$$S_a(f_m) = \frac{FkTB}{P_c} = \frac{FkT}{P_c} \quad [\text{Hz}^{-1}] \quad (1)$$

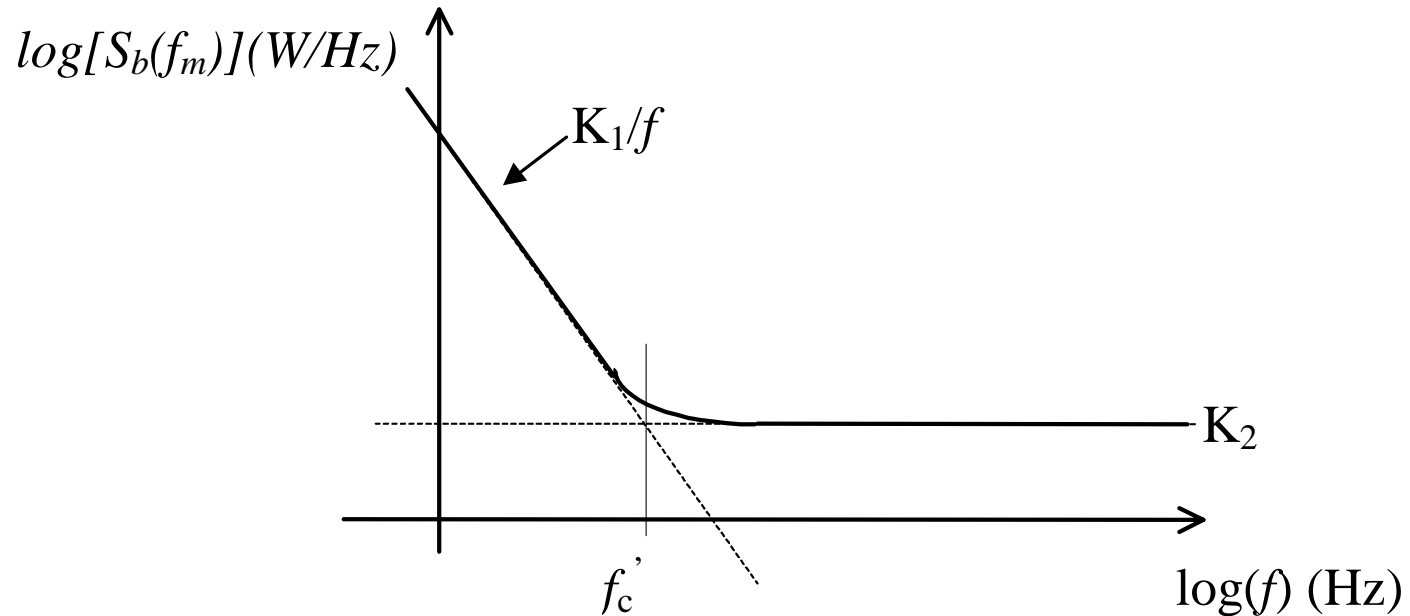
F : noise figure of the amplifier and resonator

k : Boltzmann's constant

T : Temperature in Kelvin

B : Set to 1 Hz to give $S_a(f_m)$ as **Power Spectral Density (PSD)**. Then normalize to the oscillator output power, P_c , to give the normalized PSD.

$S_b(f_m)$: Baseband noise sources upconverted by active device non-linearity.



Flicker noise ($1/f$ noise)

Shot noise (white noise)

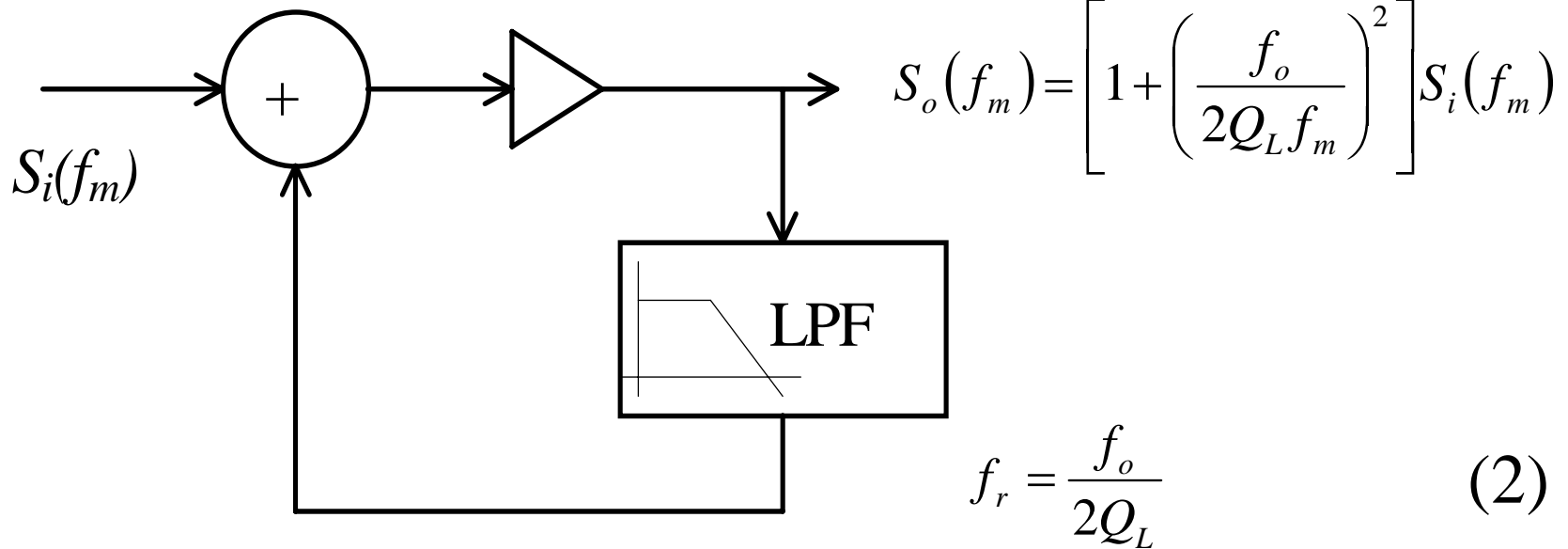
Thermal (white noise)

Transform the phase servo loop to baseband and combine normalized input noise sources:

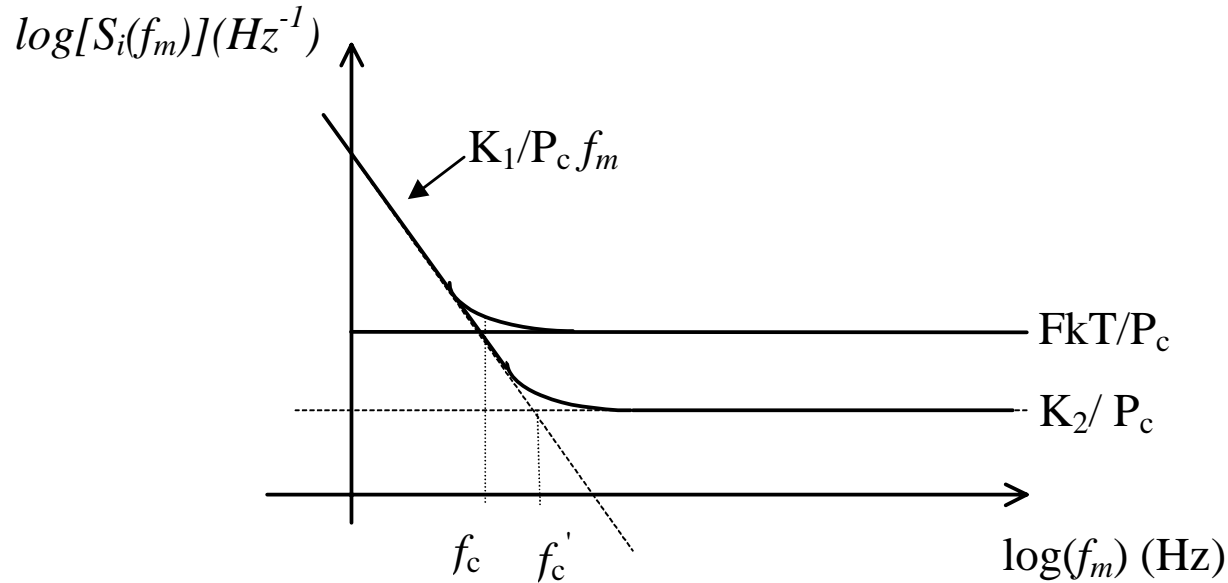
$$\text{Input PSD: } S_i(f_m) = \frac{FkT}{P_c} + \frac{K_1}{P_c f_m} + \frac{K_2}{P_c} \quad [\text{Hz}^{-1}]$$

noise-free amp
(unity gain)

Output PSD:

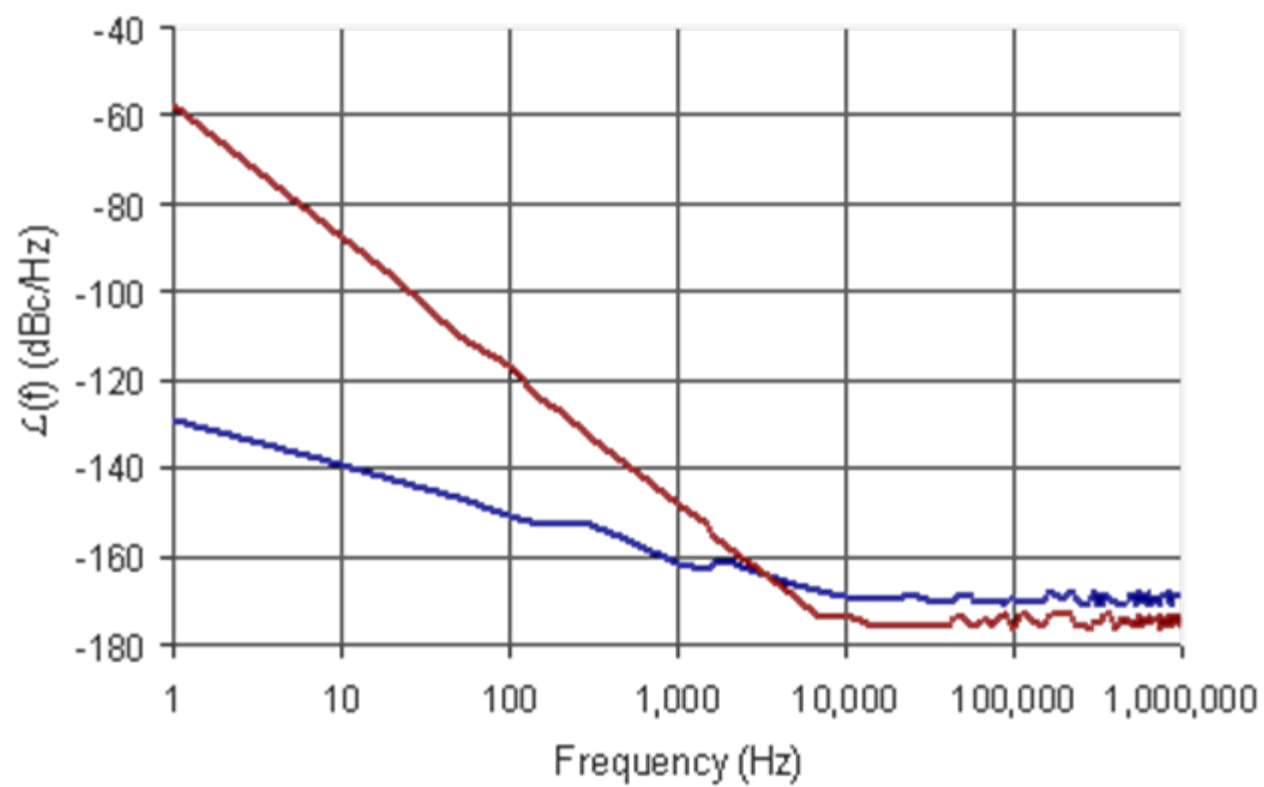


Input Noise Power Spectral Density, $S_i(f_m)$



The intersection of the K_1/f_m and FkT/P_c is the corner frequency, f_c .

$$S_i(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m} \right) [\text{Hz}^{-1}] \quad (3)$$



2. Leeson's Equation

Leeson's equation for the Power Spectral Density of an oscillator:

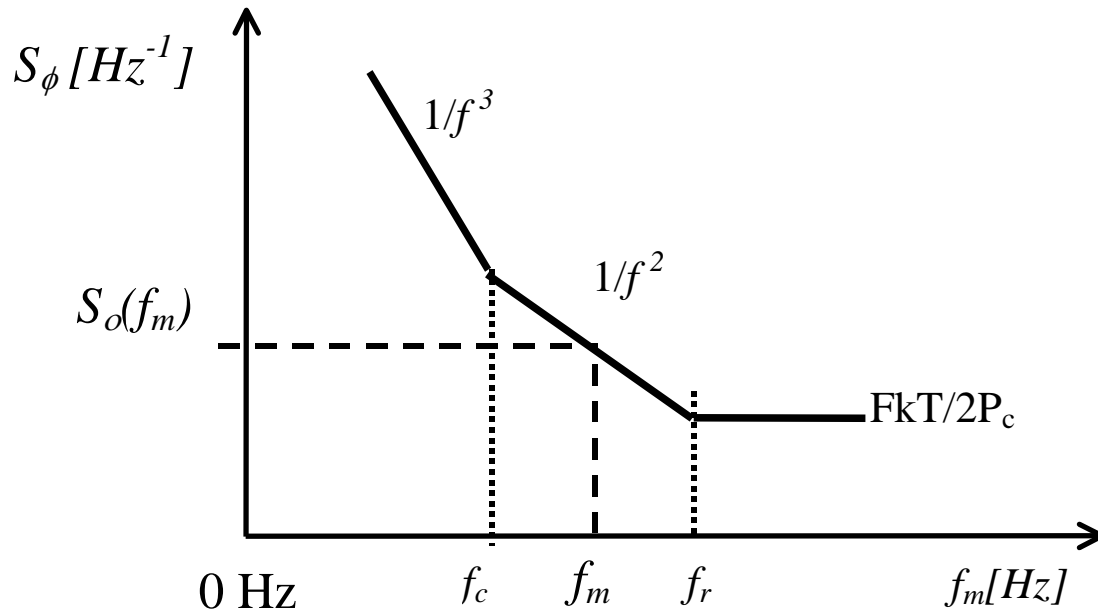
$$S_o(f_m) = \left[1 + \left(\frac{f_o}{2Q_L f_m} \right)^2 \right] S_i(f_m)$$
$$S_i(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m} \right) \quad [\text{Hz}^{-1}]$$

$$S_o(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m} \right) \left[1 + \left(\frac{f_o}{2Q_L f_m} \right)^2 \right] \quad [\text{rad}^2/\text{Hz}]$$

Equal to Spectral Density of Phase Fluctuations, $[\text{rad}^2/\text{Hz}]$, when AM noise is negligible.

2. Leeson's Equation, cont.

$$S_{\phi}(f_m) = S_o(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m}\right) \left[1 + \left(\frac{f_o}{2Q_L f_m}\right)^2\right] \quad [\text{rad}^2/\text{Hz}]$$



Single Sided Spectral Density of Phase Fluctuations, [rad²/Hz], versus offset frequency, f_m .

Using Leeson's Equation to Predict Oscillator Phase Noise

$$S_{\phi}(f_m) = S_o(f_m) = \frac{FkT}{P_c} \left(1 + \frac{f_c}{f_m}\right) \left[1 + \left(\frac{f_o}{2Q_L f_m}\right)^2\right] \text{ [rad}^2\text{/Hz]}$$

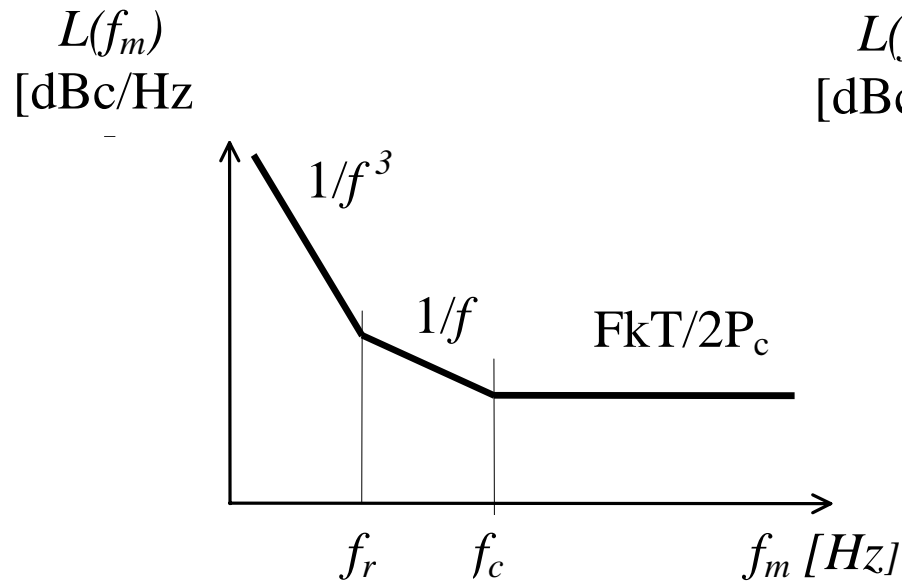
$$S_{\phi}(f_m) = 2L(f_m)$$

Oscillator resonator bandwidth: $f_r = \frac{f_o}{2Q_L}$

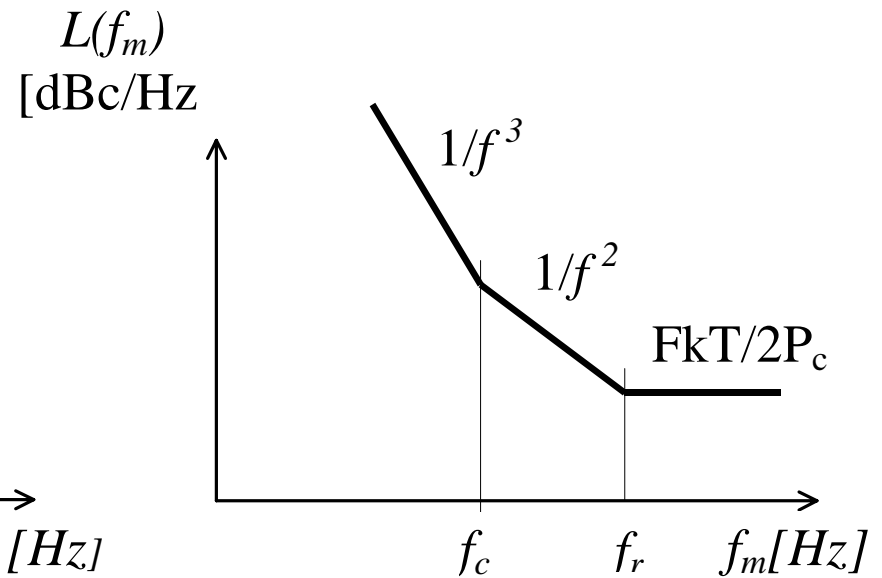
$$L(f_m) = \frac{FkT}{2P_c} \left(1 + \frac{f_c}{f_m}\right) \left[1 + \left(\frac{f_r}{f_m}\right)^2\right] \text{ [dBc/Hz]}$$

Consider two cases:

1. High-Q oscillator: $f_c > f_r$,
2. Low-Q oscillator: $f_c < f_r$.



(a) High Q -Oscillator: $f_r < f_c$



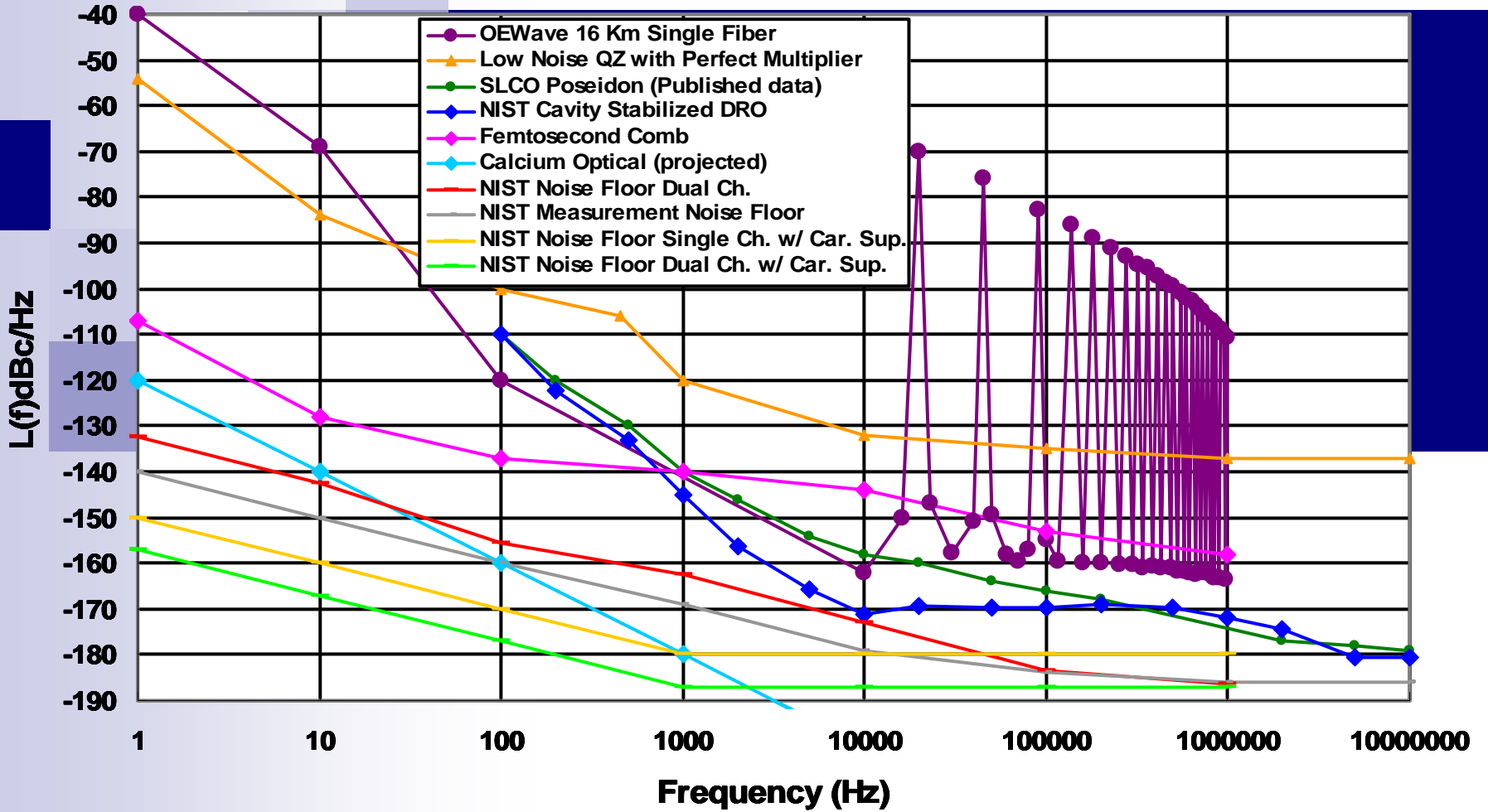
(b) Low Q -Oscillator $f_r > f_c$

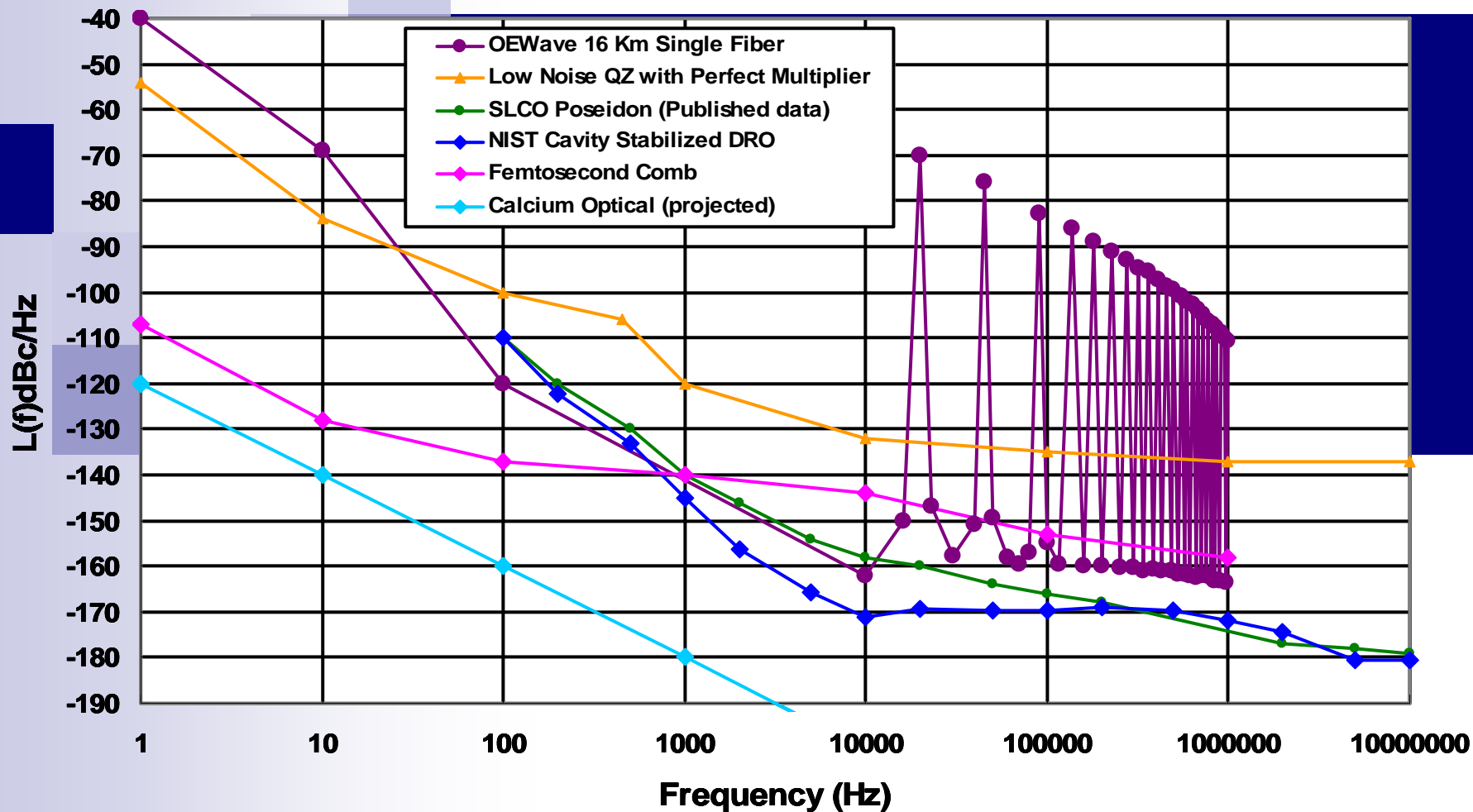
$$L(f_m) = \frac{FkT}{2P_c} \left(1 + \frac{f_c}{f_m} \right) \left[1 + \left(\frac{f_r}{f_m} \right)^2 \right]$$

$$S_\phi(f_m) = 2L(f_m) \text{ [rad}^2\text{/Hz]}$$

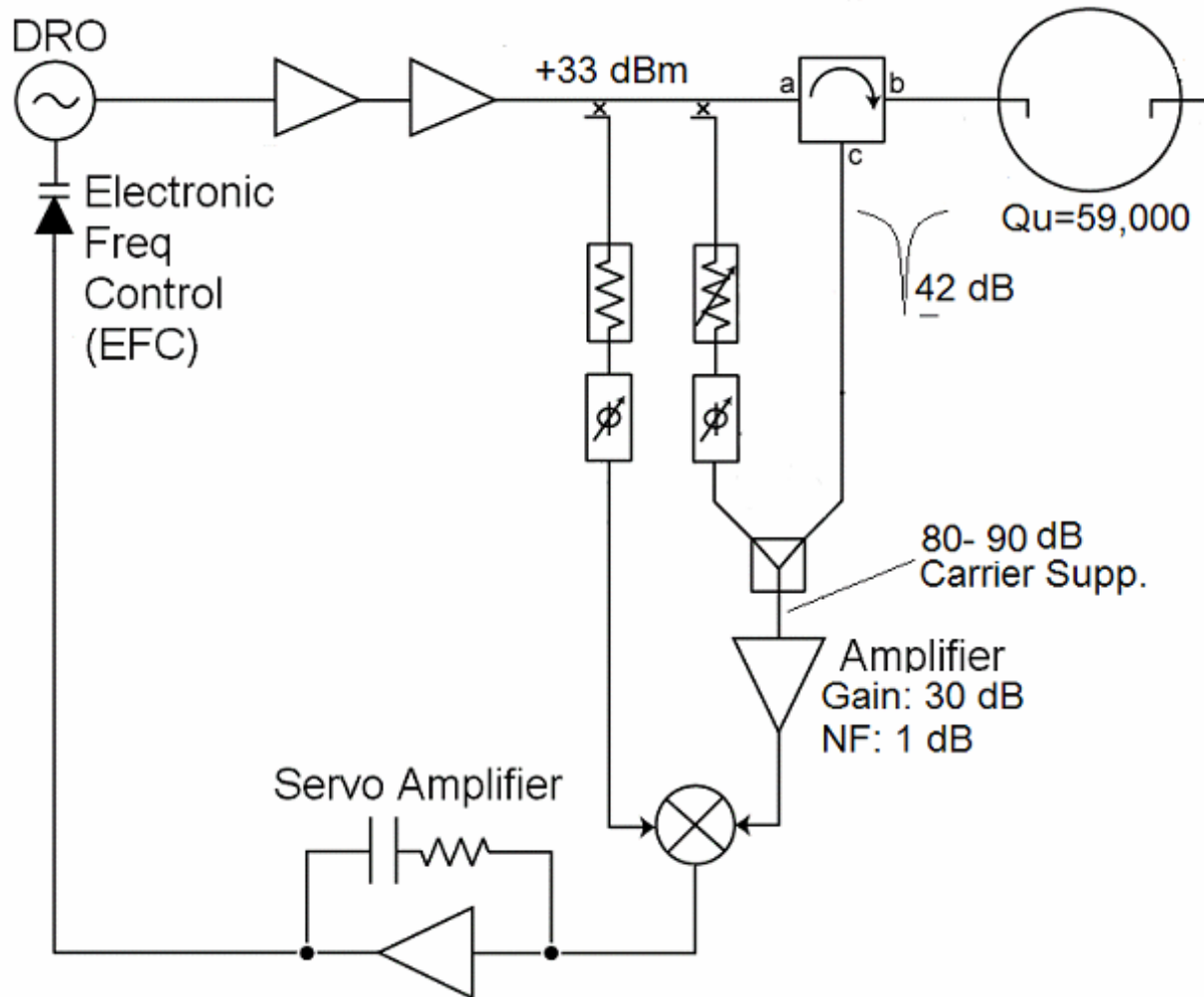
Comparison of Candidate Oscillators

Oscillator	High Power Air Cavity	SLCO Poseidon	OEO
Output coupling	Very Low	Moderate	Directional coupler and amplifier
Resonator Q	Moderate 60,000	High 190,000	Very High 1e9
Loop Power	High 1-10 Watts	Moderate 100's mW	
Inherent Spurs	None	None	Many



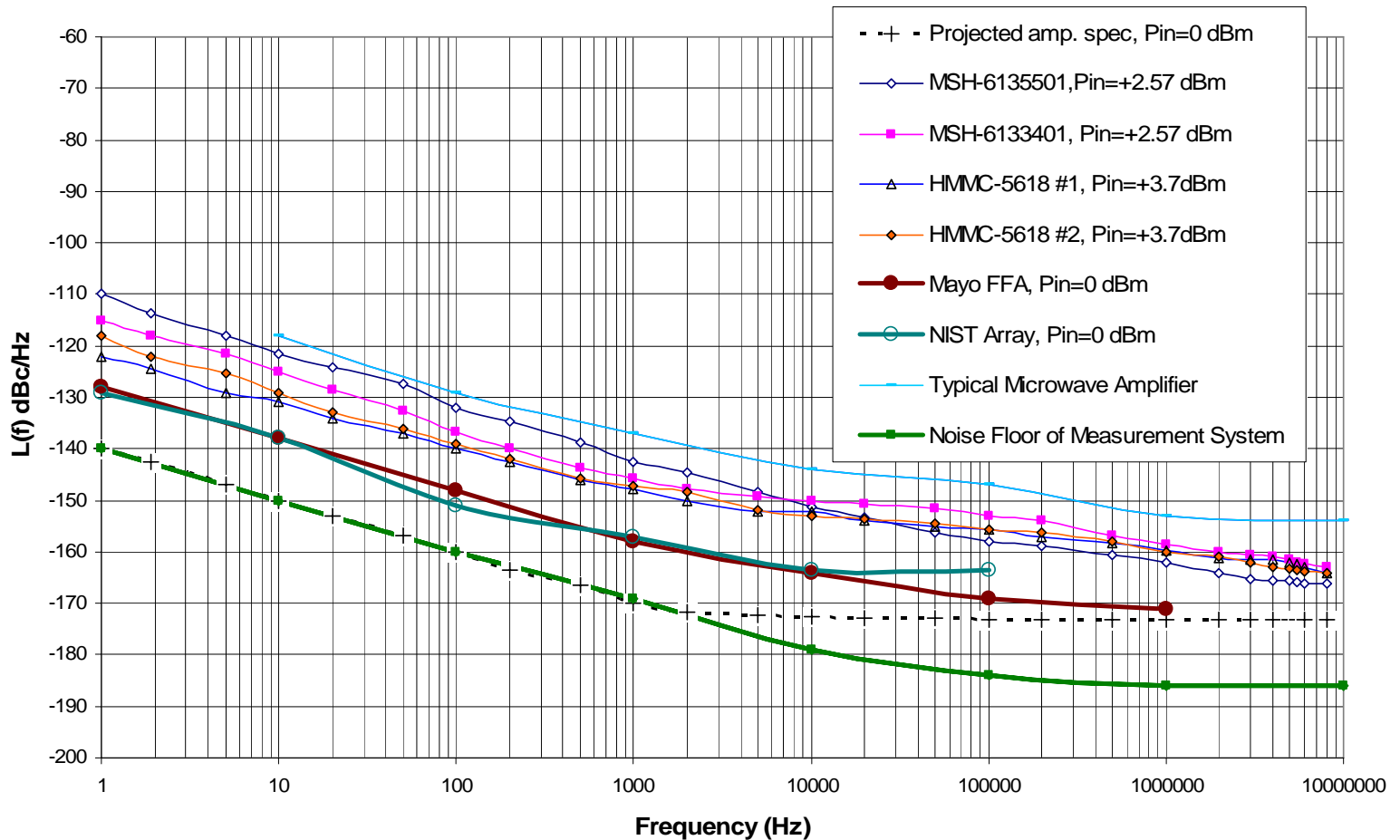


Interferometric Cavity Stabilized DRO/YIG



Amplifier Comparison

aPROPOS PM noise, goal, and four existing amplifiers (@ 10 GHz)



MAYO First Feedforward Amp Results

12/ 17/04 aPROPOS amplifier PM noise, goal (@ 10 GHz)

