Optoelectronic Microwave Generation for Achieving Ultra-low Noise and Long-term Stability

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Phase noise and frequency stability considerations

Microwave photonics combines optical generation of high quality microwave signals and microwave signal processing with optical means.

Applications require either LOW PHASE NOISE (TIME JITTER) or HIGH FREQUENCY STABILITY or both at the same time.

***APPLICATIONS*:**

- **Radar and sensing**
- **Time and frequency standard and metrology**
- **Frequency and time transfer**
- **Precision optical measurements**
- **High speed optical communication**
- **Ultra-fast all optical sampling and analog-to-digital conversion**

REQUIREMENTS

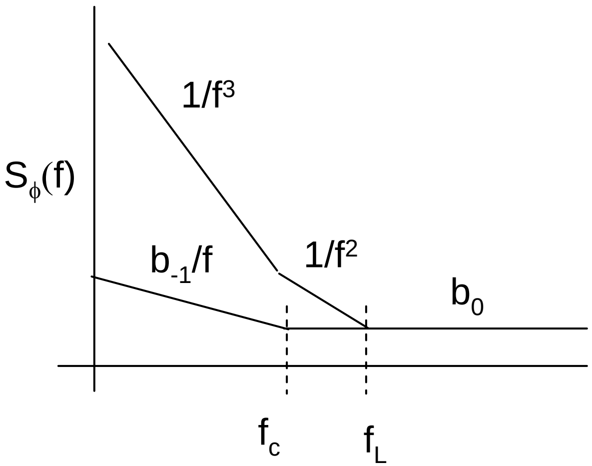
❖ High-speed: tens of GHz;
❖ Short pulse: picoseconds to sub-ps pulse width;
❖ Low time jitter: <100 fs;
❖ high frequency stability: $< 10^{-11}$

Optoelectronic Approach to High Microwave Q

Leeson formula for rf oscillator

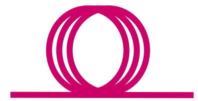
$$S_\phi^{osc}(f) = \left[1 + \frac{1}{f^2}\left(\frac{\nu_0}{2Q}\right)^2\right] S_\phi(f)$$

Leeson frequency $f_L = \frac{\nu_0}{2Q}$



D. B. Leeson, in Proc. IEEE, **54,** 329 (1966).

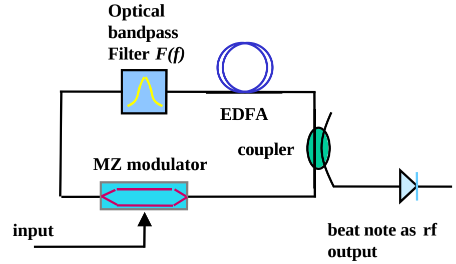
Taking advantage of optical fiber low loss transmission



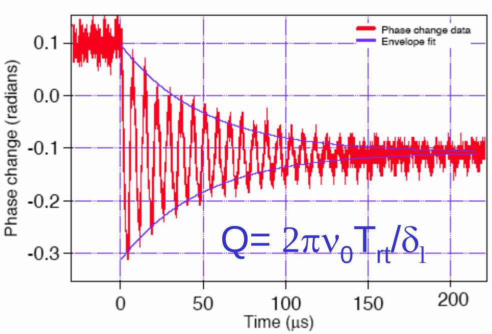
A fiber delay line offers high "resonator" Q.
1 km fiber delay is about 5 μs storage time.
$Q = 2\pi f \tau_d$
3 km fiber for 10 GHz, $Q_d \cong 10^6$

X. S. Yao and L. Maleki IEEE J. Quantum. Elect., 32, 1141(1996).

Utilizing regenerative Q in active mode-locked laser

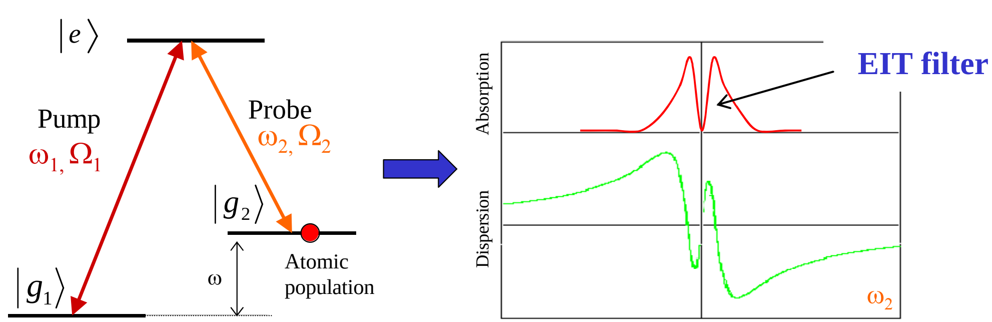


Actively mode-locked laser as two-terminal microwave device



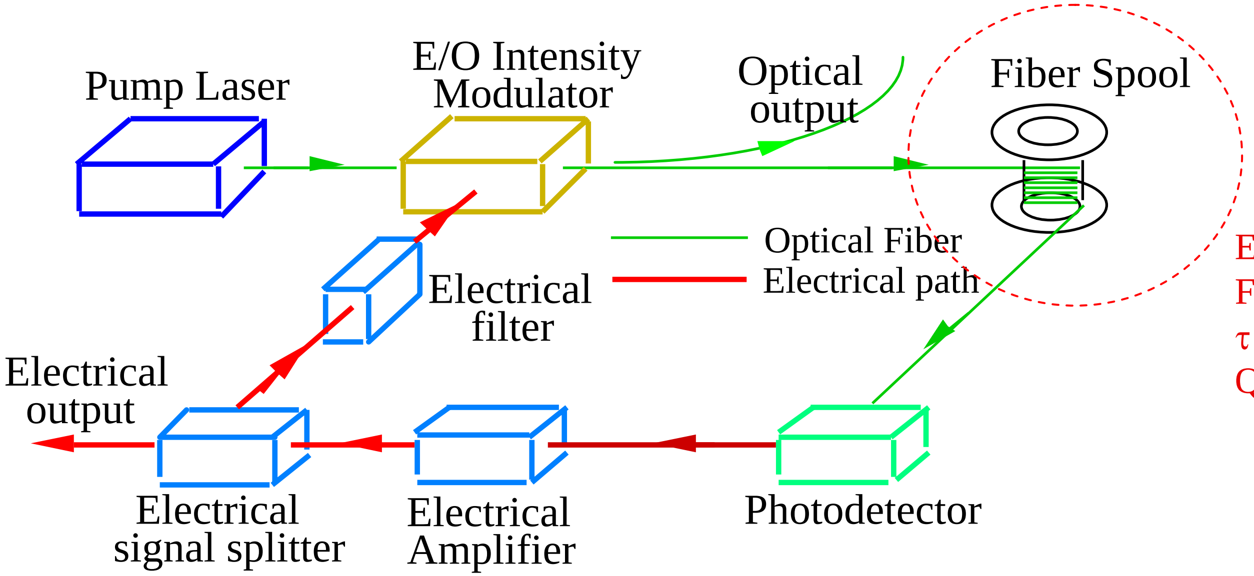
N. Yu el al. Optics Letters, Vol. 30 Issue 10 p1231 (2005).

Use filtering effect of narrow two-photon optical transition

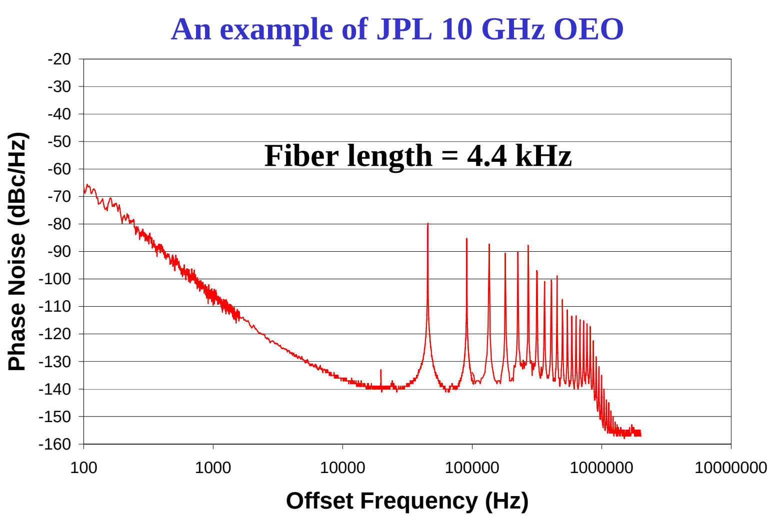


D.Strekalov,et al. J. Lightwave Technol. 21, 3052 (2003).

Optoelectronic Oscillator (OEO)



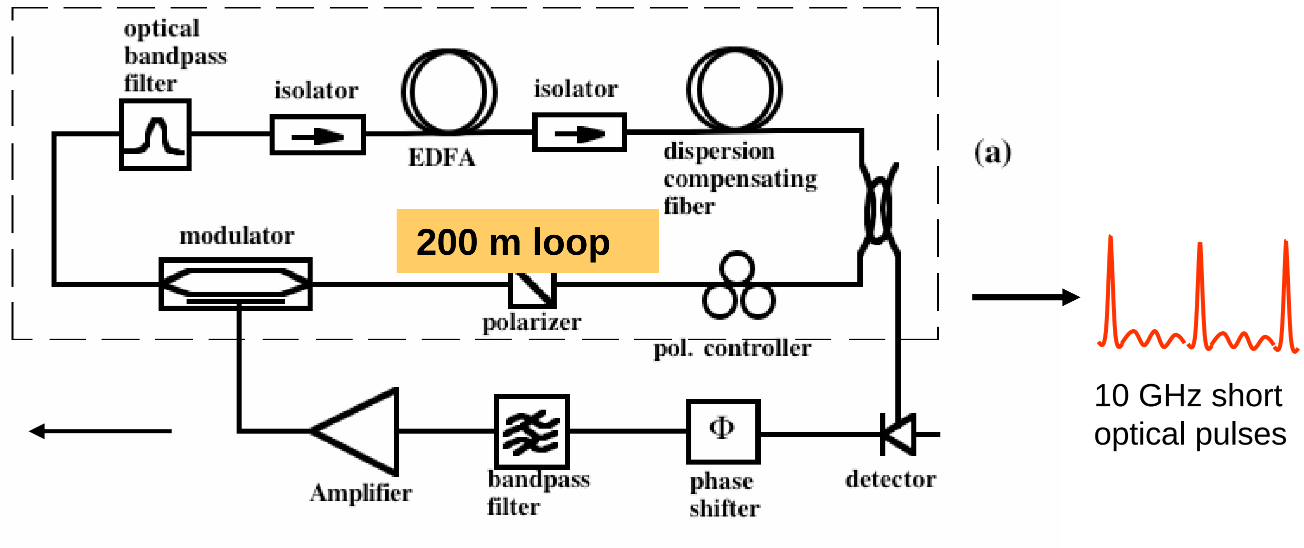
Equivalent high Q element
For a fiber length = 10 km,
$\tau \sim 50\ \mu s$ delay,
$Q=10^6$

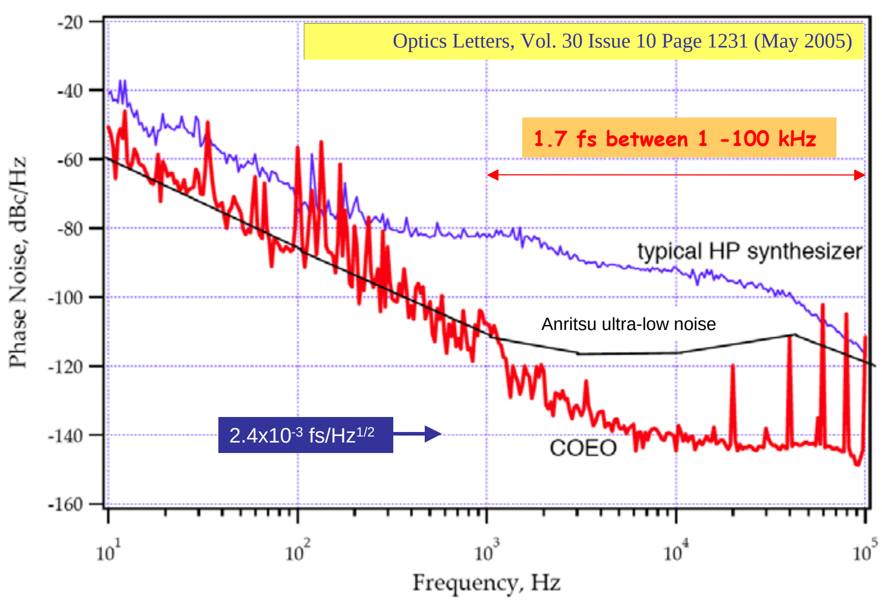


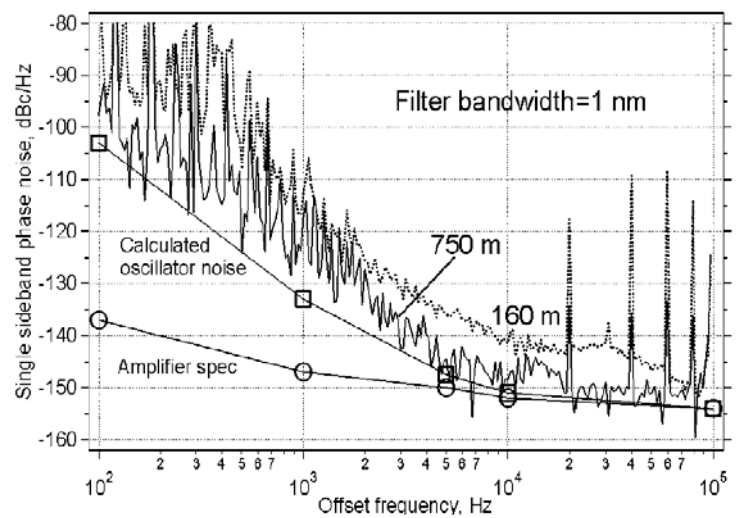
Offset Frequency	Phase Noise Achieved
10,000 Hz	-160 dBc
1000 Hz	-146 dBc
100 Hz	-120 dBc
10 Hz	-70 dBc*
1 Hz	-30 dBc*

Courtesy: Danny Eliyahu, OEwaves, Inc.

Coupled Optoelectronic Oscillator (COEO)



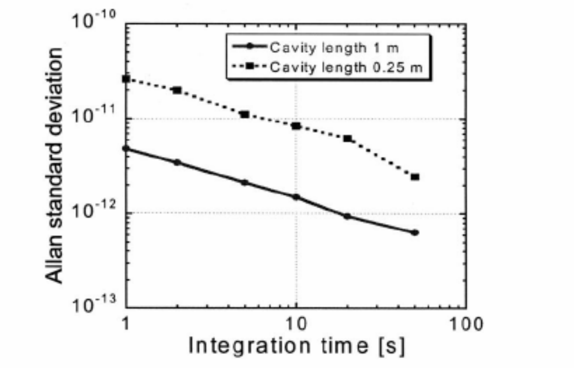




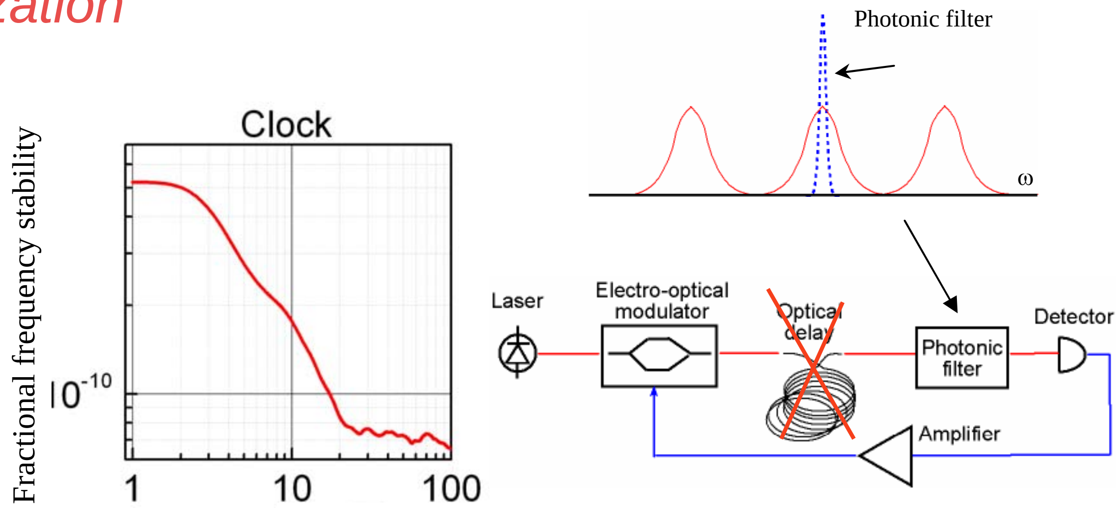
The phase noise floor of the COEO is still mostly rf-amplifier noise-limited.

Ways to improve the long-term stability

- ❑ *Passive stabilization:*
  better packaging and environmental control
- ❑ *Active stabilization to atomic transitions:*
  frequency lock to Cs microwave transition or Hydrogen Maser
- ❑ *Use atomic resonator: EIT clock*
- ❑ *Optical frequency stabilization*



Stabilized to Cs beam tube
(M. Yakabe et al. OL. V30, 1514 (2005))

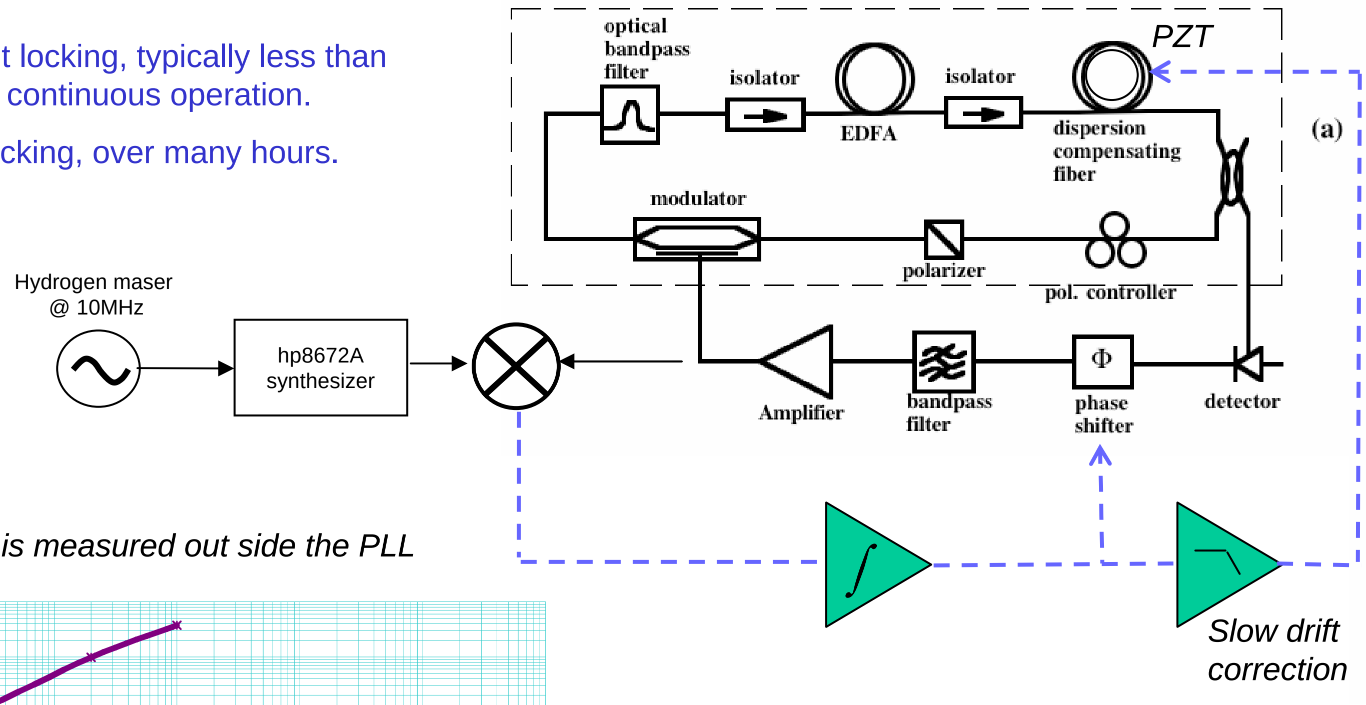


EIT stabilized OEO (D. Strekalov et al, JPL)

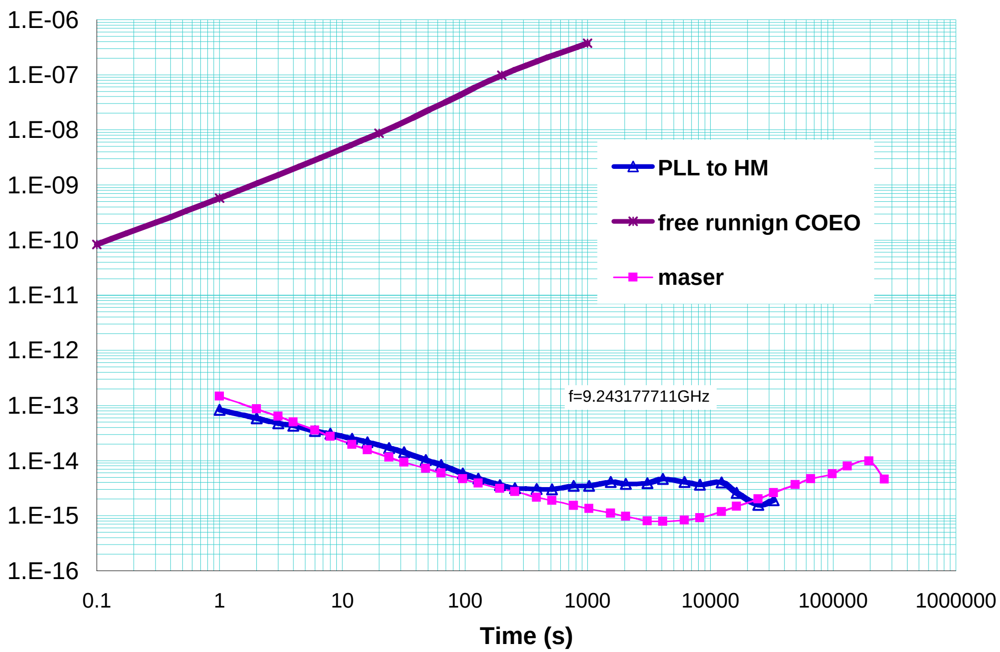
COEO Frequency Locked to Hydrogen Maser

Without locking, typically less than 60 min continuous operation.

With locking, over many hours.



Allan variance measurement is measured out side the PLL



Phase lock is achieved through a voltage controlled phase shifter in microwave loop with PZT in optical loop for long term shift.

Because of the fast response of VCP, the phase correction response can be faster than the oscillator loop response time; a useful feature for precision phase locked to other sources.

Conclusion

1. Various optoelectronic schemes can be used to obtain equivalent high microwave Q for producing ultra-low phase microwave signals. In particular, COEO with MLL as high Q element simultaneously produces ultra-low noise microwave and short optical pulses.

2. Long-term frequency stability of optoelectronic oscillators can be achieved by locking to atomic or molecular references. We have shown the frequency stabilization by locking to Hydrogen maser and by using photonic filter of atomic resonance.

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