Optical Techniques for Low-Noise Microwave Frequency Sources

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Outline

- Why Optical Techniques
  - What does a high performance oscillator require
  - Shortcomings of conventional techniques
  - Advantages of optical techniques
- Wavemixing: Advantages and Disadvantages
- Wavemixing with Feedback: The OEO
- Feedback in both loops: COEO
- Sate of the Art and Future Prospects
Oscillator Theory (Leeson Model)

A: noiseless amplifier
b: resonator with $Q = \frac{v_o}{AV}$

Frequency shift due to a phase deviation $\Delta \phi$:

$$\frac{\Delta f}{f_o} = \frac{\Delta \phi}{2Q}$$

Loop phase noise spectrum $S_\phi(f)$

Within the resonator bandwidth, the oscillator phase noise spectrum

$$S_\phi^w(f) = \frac{1}{f^2} \left( \frac{v_o}{2Q} \right)^2 S_\phi(f)$$

Outside the resonator bandwidth:

$$S_\phi^o(f) = S_\phi(f)$$

Leeson model

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

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

Conventional Approaches for High performance Microwave Oscillators

- Start with a good quartz oscillator at ~ 100 MHz and multiply up
  - Noise also multiplies at 20 logN with N the multiplication factor
  - Usually complex chains, requiring low noise amplifiers, mixers, etc.
- Use a high-Q microwave cavity
  - Q degrades with frequency (QF~ a constant)
  - High Q cavities sensitive to environmental perturbations
- Highest spectral purity at $f > 10$ GHz obtained only sapphire or air-gap cavities: large power consumption, and large size (shoe-box and larger)
- Susceptible to EMI
- Can't meet high end applications' requirements for temperature stability, acceleration sensitivity, etc. without adding to mass/size
Why Optical Techniques

- Microwave signal is generated by photomixing of two or more optical frequencies, or sidebands
  - Not limited by RF components (except amplifiers)
  - Can be made at any microwave frequency
  - Approaches available for tuning with high performance optical filters
- Loss for these sidebands is about the same regardless of the sideband frequency, thus Q does not degrade
- Optical guides, cavities and filters have intrinsically lower loss than microwave counterparts
- Because of the small optical wavelengths, optical devices are intrinsically small

Basic Photonic RF links

**Directly modulated Link**
RF signal directly drives the laser

**Externally modulated link**
RF signal drives an E/O modulator external to the laser

Lower dynamic range
most CATV systems

High dynamic range
High performance systems
Commonly used lasers for RF systems

- Distributed Bragg Reflector (DBR) Laser
  - Bragg gratings are narrow band reflectors
  - Optical feedback through grating reflection
  - Single/multimode operation

- Diode-pumped solid-state laser
  - Solid-state gain medium pumped by diode lasers
  - Narrow spectral width
  - Lowest noise
  - Most reliable
  - Less reliable

- Fabry-Perot laser (F-P laser)
  - Optical feedback provided by the end mirrors
  - Multi-longitudinal modes
  - Higher noise due to mode competition

- Distributed feedback laser (DFB laser)
  - Optical feedback provided by the grating on top of the gain medium
  - Single-longitudinal mode
  - Lower noise

Commonly used Photodetectors

- InGaAs PIN photodiodes (0.8 - 1.7 um)
  - High responsivity: up to 0.95 A/W commercially available
  - High saturation power: up to 15 mW commercially available
  - High speed: up to 25 GHz commercially available
  - Lowest dark current: >0.1 nA (intrinsic noise)

- InGaAs Schottky photodiodes (0.95 - 1.65 um)
  - Lower responsivity: ~0.4 A/W
  - Highest speed: 60 GHz commercially available
  - Low saturation power: ~2 mW

- Ge PIN photodiodes (0.8 - 1.8 um)
  - High responsivity: ~0.9 A/W
  - Higher dark current: ~1 nA
Common Modulators

<table>
<thead>
<tr>
<th>Modulator Type</th>
<th>Optical Inputs</th>
<th>Optical Outputs</th>
<th>RF Input</th>
<th>Bandwidth</th>
<th>Linearity</th>
<th>Chirp</th>
<th>Drive Voltage</th>
<th>Insertion Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-absorption modulator</td>
<td>Optical in</td>
<td>Optical outs</td>
<td>RF in</td>
<td>Wide Bandwidth: up to 100 GHz</td>
<td>Good linearity</td>
<td>No chirp (good)</td>
<td>High drive voltage</td>
<td>High RF insertion loss</td>
</tr>
<tr>
<td>Mach-Zehnder modulator</td>
<td>Optical in</td>
<td>Optical outs</td>
<td>RF in</td>
<td>* Potential large Bandwidth</td>
<td>* Not well developed</td>
<td>* Not as good linearity</td>
<td>* Modulation chirp</td>
<td>* High drive voltage</td>
</tr>
<tr>
<td>Directional coupler modulator</td>
<td>Optical in</td>
<td>Optical outs</td>
<td>RF in</td>
<td>* Potential large Bandwidth</td>
<td>* Not well developed</td>
<td>* Not as good linearity</td>
<td>* Modulation chirp</td>
<td>* High drive voltage</td>
</tr>
<tr>
<td>Laser optical coupler modulator</td>
<td>Laser</td>
<td>Optical out</td>
<td>RF in</td>
<td>* Wideband width: &gt; 60 GHz</td>
<td>* Easy integration with diode lasers</td>
<td>* Extremely compact</td>
<td>* Low drive voltage</td>
<td>Modulation chirp (not good)</td>
</tr>
</tbody>
</table>

Other photonic devices

- Directional couplers (ratio: 1 - 50%, backreflection < -65 dB)
- Isolators (insertion loss: < 0.6 dB, isolation > 40 dB)
- Circulators (insertion loss: < 0.8 dB, isolation > 40 dB)
- Polarizers (insertion loss: < 0.4 dB, backreflection < -60 dB)
- Polarization controllers (no loss, no backreflection)
- Filters (insertion loss < 0.5 dB, BW: 0.8 nm and up)
- Faraday polarization rotator and mirror
- Connectors: Physical contact (PC) and angled physical contact (APC)
  - loss < 0.25 dB, backreflection: PC < -40 dB, APC < -65 dB
- Fiber optic amplifiers: doped fiber & semiconductor
Photodetector as a mixer

Power Law Photodetector \( \Leftrightarrow \) acts as a mixer

\[
\text{Photocurrent } I = I_0 I_0^* \\
(Asin2\pi f_1 + Bsin2\pi f_2)^2 \Leftrightarrow (f_1 + f_2) \text{ and } (f_1 - f_2)
\]

Features of Signals Generated by Photomixing of Lasers

- Simple approach requiring two lasers with narrow linewidth
- Can be used with lasers that are phase, frequency, or injection locked
- Highly tunable over a long range
- The microwave beat signal limited by laser linewidth, set by lasers or by lock oscillators
Example of a High Frequency Beat Note generator


- Spontaneous emission is a noise with white frequency character, and a linewidth "Schalow-Townes" that is:

\[ \Delta \nu_{ST} = \left( \frac{\alpha h c^2}{4 \pi} \right) \frac{T^2 \nu}{L^2 P_{out}} \]

\[ \Delta \nu = \pi S_f^2 \], so that we have: \[ L(f) = \frac{S_f^2}{2 f^2} \]
Opto-Electronic Feedback

- Start with a Photonic link

[Diagram of a Photonic link with PD and HA]

- Close the loop with gain and in phase

[Diagram of an Integrated Laser/Modulator with E/A modulator, Optical out, Laser, Fiber, and OEO]

OEO

- OEO is a generic device: various configurations of lasers, modulators, optical delays can be implemented
- OEO lends itself to diverse architectures (dual loop, Coupled OEO, etc) to support diverse applications
- OEO’s performance will improve with improved components (amplifiers, lasers, modulators, detectors, optical delays)
- OEO is ideal for opto-electronic integration
- The OEO signal is available both electrically, and on an optical carrier
- The COEO version generates short (sub-picosecond) optical pulses with lowest jitter
- OEO cab be phase locked, frequency locked, self locked, and used as a VCO
- The microresonator based OEO has a small size, low power consumption and intrinsically low acceleration sensitivity
- Unique microresonator based optical filter enables widely tunable oscillator
OEO vs. van der Pol Oscillator

van der Pol Oscillator

Opto-electronic Oscillator

kHz

Optical Fiber

Electrical path

Electrical output

Electrical signal splitter

Electrical Amplifier

Photodetector

High Q & High Frequency

Low Q & Low Frequency

kHz to > 70 GHz

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OEO Features

- High Q resulting from the low loss fiber \(\Rightarrow\) Low phase noise
- High frequency resulting from fast photonic devices
- Widely tunable
- Both electrical & optical outputs \(\Rightarrow\) No E/O & O/E conversion required
- Can be locked to a master reference either optically or electrically
- Meets the requirements of RF photonics systems

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Important characteristics of the OEO

- **High spectral purity** due to long optical storage time provided by the fiber in a closed loop.
- The quality factor (RF $Q \sim 10^5-10^6$) is proportional to the oscillation frequency, leading to **noise level performance that is independent of frequency**.
- The mode spacing is related to the inverse of loop trip time: $\approx \frac{c}{n \cdot L}$
  
  where $c$ is the speed of light, $n$ is the fiber refractive index and $L$ is the fiber length.

OEO

Some significant features

- **OEO** is a generic device: various configurations of lasers, modulators, optical delays can be implemented
- **OEO** lends itself to various architectures (dual loop, Coupled OEO, etc) to support diverse applications
- **OEO**'s performance will improve with improved components (lasers, modulators, detectors, optical delays)
- **OEO** is ideal for opto-electronic integration
- The OEO signal is available both electrically, and on an optical carrier
- The COEO version generates short (sub-picosecond) mode locked optical pulses with lowest jitter
\[ \Delta f = \frac{1}{2\pi} \frac{\delta}{t^2} \]

\[ Q = \frac{f_0}{\Delta f} = \frac{2\pi r^2}{\delta} \]

\[ S_{rf}(f) = \frac{\delta}{(\delta/2\pi)^2 + (2\pi)^2 (f/\tau)^2} \]

\[ \delta = \rho_{in} G / P_o \]

\( \tau \): Loop time delay

\( f \): Frequency offset

\( P_o \): Oscillation Power

\( \rho_{in} \) = Input noise power density

\( \rho_{in} = \) Thermal noise + Shot noise + Laser RIN noise

* Noise decays with \( f \): 20 dB/Decade

* Noise decays with \( \tau \): 20 dB/Decade

* Noise is independent of oscillation frequency \( f_o \).

* \( Q \) increases with \( f_o \).

Noise Sources and Effect on Phase Noise

For OEO with 2km Fiber Length
Typical phase noise of an OEO (10GHz)

Other performance characteristics of the OEO

- Fixed frequency from MHz to 40GHz and beyond.
- Harmonics −40dBc.
- Frequency vs. temperature slope of −0.1ppm/°C.
- Allan deviation of 2⋅10^{-11} at 1sec.
- Frequency stability of 0.02ppm over 1 hour.
- Phase locking achievable through VCP.
- Vibration and acceleration sensitivity at 10^{-10}/g.
Multi-loop tunable OEO

YIG tunable OEO – phase noise

OEO phase noise level that is better by ~30dB compared with any commercial free running YIG tunable oscillator
Packaged OEO with Vibration Compensation

- Packaged OEO with vibration compensation (reduced the acceleration sensitivity).

| Vibration Test Results (without fiber delay line compensation) | OEO 2.7 GHz, 1.1 km, 10 MHz, 20 °C, 14 °C |
|---|---|---|---|---|
| 1 | 0.123 | 0.050 | 32.755 | 32.324 |
| 3 | 0.050 | 0.040 | 33.755 | 32.948 |
| 4 | 0.050 | 0.040 | 32.845 | 31.857 |
| 5 | 0.050 | 0.040 | 33.845 | 33.857 |
| Average | 0.050 | 0.040 | 32.719 | 32.744 |

Phase Noise
(f_c=6.12GHz, with 4km fiber as the testing delay line)

Advantages:
* Dual electrical & optical outputs
* High spectral purity, low phase noise
* Frequency up to 100 GHz
* Compact & potentially low cost
* Tunable & VCO
* Eliminate external LO => lower cost

OEO and Optical distribution of Reference Signal

**Advantages:**
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**No external LO needed**

Transmitting

Receiving

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Microsphere -- a low-loss photon trap, novel optical (micro)cavity

Whispering-gallery modes - closed circular waves under total internal reflection

(Term by J.W.S. Rayleigh, analogy to acoustic modes in the gallery of St Paul cathedral)

Sustained in any axisymmetric dielectric body with \( R \geq 2 \lambda \)

- low material loss (transparent material, e.g. fiber grade silica)
- low bending loss (\( R \gg 2 \lambda \))
- low scattering loss (TIR always under grazing incidence
  + molecular-size surface roughness)

| Quality-factor \( Q = \frac{\lambda}{\Delta \lambda_{\text{RES}}} \) | \( \text{up to } \sim 10^{10} \) |
| Photon lifetime \( \tau = \frac{\lambda Q}{2 \pi c} \) | \( \text{up to } \sim 3 \mu s \) |
| (cavity ringdown time) | |

Visualization of WG mode field by residual scattering in silica microsphere, V.S. Ilchenko et al. OptComun. 113, p.133(1994)

Opto-electronic Oscillator on Chip

Electro-absorption modulator section

Gain section

Microsphere

HR

RF output

Optical output

A gap to induce reflection

Gain section

Photodetector (reversely biased electro-absorption modulator)

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COEO

Opto-electronic oscillator (OEO): ultra-low phase noise

Coupled OEO (COEO)

Er+ doped fiber amplifier (EDFA) mode-locked laser: ps pulse train generation

Approach 1: Direct phase-locked MLL

Approach 2: Cavity-based OEO: higher stability possible

Optical-microwave frequency stability transfer

Ultra-low jitter optical pulse trains

Applications:

Ultra-fast fiber communication

Fast sampling and optical analog-to-digital conversion

Precision optical measurement and opto-electronic material research

Ultra-low phase noise amplifier

Mode-locked Laser (MLL), Opto-electronic Oscillator (OEO) and Coupled Opto-electronic Oscillator (COEO)

10 GHz low phase noise microwave

(a) COEO

(b) OEO

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Locking modes

Picosecond pulse

2 ps pulse every ~100 ps
Coupled opto-electronic oscillator

Measured Phase Noise of the COEO
Small Signal and off-Resonance Responses

Figure 2. The measured microwave frequency response of the phase step. A Lorentzian fit gives 8.5 kHz FWHM.

Experimental Verification of Leeson Frequency

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Noises in the Mode-locked Laser As Filter

Noises in the mode-locked laser as a filter are:
1. Photon shot noise power $S_p(f) = 1/N$. Typical optical power at detector 1 mW, $N=10^{16}$, $S_p(f) = -160$ dBc.
2. Spontaneous emission, one photon per cycle/Hz per second, $N_0 = 1.3 \times 10^{15}$ W/Hz = -160 dBm/Hz.
3. For comparison, amplifier thermal noise $K_T = -174$ dBm/Hz.

Equivalent phase noise of the MLL laser as an rf filter:
The regenerative process in the loop amplifies the spontaneous emission by $G$, within the regenerative bandwidth with the gain-bandwidth product a constant $\Delta f$.

$S_{\phi}(f) = (\Delta f/\Delta f_{\phi})^2$

Relative high circulating optical power and free of flicker noise.

Analysis of the Measured Oscillator Phase Noise

Phase noise as a function of frequency is shown with different components: shot noise, amplifier flicker (measured), and ASE. The $1/f$ component is prominent at low frequencies.

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The frequency of a mode is simply
\[ F_N = N \times f_{\text{rep}} - \frac{f_0}{\tau_{\text{rep}}} \]

where \( N \) is an integer and \( f_0 \) is the free spectral range.

\[ f_0 \approx 1000 \text{ MHz} \]

\( f_r = 1/\tau_{\text{rep}} \)
Optical Clock with a Femtosecond Synthesizer


IEEE JQE, Dec (2001)
IEEE JSTQE (Apr 2003)

Hyper-parametric oscillations in fluorite resonators

Selection rules
FWM: TE-TE
SRS: TE-TM

Optical spectrum

\[ Q = 2 \times 10^{10} \text{ at } \lambda = 1310 \text{ nm} \]
Microwave beat note observed

- Second-order \( (2\Omega_{\text{SR}}) \) beat note is insignificant
- Raman scattering is not observed (expected at 322 cm\(^{-1}\))

A.A. Savchenkov et al.,
Submitted to PRL (2004)

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Noise sources in photonic systems

- Thermal noise: \( kT \)
- Shot noise: \( 2\Delta R \)
- Laser RIN (relative intensity noise): \( <\Delta P^2>/P^2 \)
- \( 1/f \) RIN (at \(< 10 \) kHz)
- Relaxation oscillation RIN peak
- Interferometric noise
- Double Rayleigh scattering noise
- Brillouin scattering caused noise
- Fiber dispersion mediated noise
- Fiber thermal noise
White Noise

![White Noise Graph]

1/f RIN & Relaxation Oscillation RIN

![1/f RIN & Relaxation Oscillation Graph]

* The low frequency 1/f noise & relaxation oscillation peak will be multiplied up by the modulator & affect the signal.
Fiber thermal fluctuation noise

Just like Johnson's noise, fiber's refractive index fluctuates with $kT$.

First studied by fiber gyro researchers.

For 9/125 um fiber @ 1.3 um:

$$\frac{\Delta f}{f} = \frac{\Delta L}{L} \sim 10^{-12}/L^{1/2}$$

$L = 100$ m $\Rightarrow \Delta f/f \sim 10^{-13}$

$L = 10$ km $\Rightarrow \Delta f/f \sim 10^{-14}$

Fiber dispersion mediated noise

Dispersion: different light frequency "see" different fiber lengths.

Optical frequency fluctuation $\Rightarrow$ RF phase fluctuation.

For standard single mode fiber, 1 nm away from zero dispersion:

$$\frac{\Delta f}{f} = \frac{\Delta L}{L} \sim 0.6 \times 10^{-5} \Delta \nu/\nu$$

$\Delta \nu/\nu$: laser frequency stability.

$\Delta \nu/\nu = 10^{-10} \Rightarrow \Delta f/f = 6 \times 10^{-15}$

APPENDIX

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Advantages of Optical Fiber

- Wide Bandwidth $\Rightarrow$ High frequency
  - 20 MHz-km (multimode) to $>100$ GHz-km (single mode)
  - With wavelength division multiplexing, $>1$ Tbps over 600 km demonstrated.
- Low Loss $\Rightarrow$ High Q delay line for low phase noise
  - $\sim0.5$ dB/km @ 1300 nm, 0.2 dB/km @ 1550 nm
- Low thermal-induced delay change $\Rightarrow$ High stability
  - Single mode fiber: 7 ppm/^\circ C, Special fiber: $<0.1$ ppm/^\circ C
- No RFI or EMI problems $\Rightarrow$ Immune to spurious noise sources
- Electrical isolation between ends
- No ground loops
- Small, lightweight, & corrosion resistant
- Material is plentiful & inexpensive
- Cost/capacity ratio is extremely low

How Fiber Works

Snell Law

Reflection

Mirror

$P_0$ $\Rightarrow$ Loss

All mirrored surfaces have loss!!

Total Internal Reflection

$P_0$ Critical angle

$n_1$ (Low index of refraction)

$n_2$ (High index of refraction)

No Loss!!

$* \quad n = c/v$

$c$ = the speed of light in a vacuum ($3 \times 10^8$ m/s)

$v$ = the speed of light in the material ($\sim 2 \times 10^8$ m/s in glass)

$* \quad$ The index of refraction of glass can be changed by adding impurities (doping)
Basics of Optical Fiber

History

- 1910: Concept conceived by Hondros & Debye
- 1915: Existence of a dielectrically guided wave demonstrated by Zahn, Ruter & Schriever
- 1959: Waveguide modes in optical fiber observed by Snitzer & Hicks.
- 1965: Fibers with a loss less than 20-dB/km for fiber optic communications proposed by Kao.
- 1970: Practical fiber with 20 dB/km loss announced by Kapron, Keck, & Maurer.
- 1972: 4 dB/km loss fiber developed by Corning.
- Today: Fiber has a loss of 0.2 dB/km @ 1550 nm