Integrated RF-Photonics

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<table>
<thead>
<tr>
<th>Docket #</th>
<th>Title</th>
<th>Filed date</th>
<th>Publication S/N</th>
<th>Issue date</th>
<th>US Patent #</th>
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<tr>
<td>C 5227</td>
<td>Tunable Heavy and light hole coupled bands in Variable Strained OW semiconductor heterostructure for novel OE device</td>
<td>05/02/1995</td>
<td>5412225</td>
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<td>Modulation doped quantum well modulator</td>
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<td>C 5381</td>
<td>Method of making monolithically integrated signal processing circuit having active and passive components</td>
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<td>C 5253</td>
<td>Monolithically integrated signal processing circuit having active and passive components</td>
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<td>Tilted Valence-band quantum well double heterostructures for single step optical waveguide device monolithic integration</td>
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<td>C5420</td>
<td>Microwave Systems</td>
<td>2/13/2001</td>
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<td>01-32</td>
<td>Simple True-time-delay generation for optical control of phased array antenna</td>
<td>05/14/2002</td>
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<td>03-30</td>
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<td>02/10/2004</td>
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<td>Reconfigurable photonic band gap device for integrated optoelectronics</td>
<td>3/05/04</td>
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<td>04-74</td>
<td>Method of constructing a reconfigurable photonic bandgap device</td>
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<td>04-74</td>
<td>Electro optical scanning multi-function antenna</td>
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<td>RF to Optical converter for RF imaging with optical sensors</td>
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<td>12/754681</td>
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<td>Method of constructing a semiconductor hollow-core waveguide using high-contrast gratings</td>
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<td>Method of constructing a RF microwave true time domain cross-correlation receiver as pulsed Doppler radar receiver using photonics</td>
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<td>09-02</td>
<td>Searching, tracking, selecting prioritizing and identifying target by using a pulsed radar system with a RF microwave true time domain correlation receiver</td>
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<td>15-36</td>
<td>RF-Photonic Pulse Doppler Radar</td>
<td>3/7/2017</td>
<td>15/451456</td>
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<td>15-38</td>
<td>Opto-electronic Oscillator with Stimulated Brillouin Scattering feedback</td>
<td>3/7/2017</td>
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What is RF-Photonics?

Using Photonics to:
- Generate
- Transport
- Transmit
- Receive
- Distribute
- Processing

RF Signals (microwave, MMW, THz)

Applications
- Precision Oscillator
- Precision Clock
- Radar (w/special function)
- Spectrum Analyzer (wideband, for short pulse)
- Correlation receiver
- Signal Processing
- Positioning/Navigation/Timing
- Acoustic sensing
- EW
- ...

The Nation’s Premier Laboratory for Land Forces
A typical RF system:

Integrated Photonic Modules
(reduce number by n)
OptoElectronic Oscillator (OEO) & Optical Frequency Comb (OFC)

- Generating Ultra-high Precision Frequency with long time stability (Time)
**Why OEO**

**Comparison of OEO with Poseidon and 10 MHz OCXO**

<table>
<thead>
<tr>
<th>Oscillator type</th>
<th>Cavity/length</th>
<th>Unloaded Q @10GHz</th>
<th>Loaded Q</th>
<th>Phase noise @1KHz</th>
<th>remark</th>
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<tbody>
<tr>
<td>DIL-OEO (0-100GHz)</td>
<td>5.5 km fiber</td>
<td>$1.5 \times 10^6$</td>
<td>?</td>
<td>$-115$ dBc/Hz (exp)</td>
<td>Naked oscillator</td>
</tr>
<tr>
<td></td>
<td>9 km fiber</td>
<td>$2.5 \times 10^6$</td>
<td>?</td>
<td>$-160$ dBc/Hz (ideal)</td>
<td>Naked oscillator</td>
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<tr>
<td>Poseidon</td>
<td>Sapphire loop</td>
<td>$1.3 \times 10^5$</td>
<td>$0.8 \times 10^5$</td>
<td>$-130$ dBc/Hz (exp)</td>
<td>Feedback circuit Temperature control</td>
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<tr>
<td>OCXO (10MHz)</td>
<td>Quartz</td>
<td>$10^6$ @ 5 MHz</td>
<td>$\sim 10^6$</td>
<td>$-155$ dBc/Hz (exp w/10MHz carrier)</td>
<td>Feedback circuit Temperature control</td>
</tr>
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</table>

**Q is the limit for the close-in phase noise floor**

**The OEO has unutilized Q**

- fiber length dependent noise dominates after 5km

**The Poseidon is near its Q-limit**

**OCXO has reached its limit**

**The OEO can also go to high frequency to obtain higher Q**

**OEO has a lot more potential to lower the phase noise!**
Objective: Find optimum configuration /condition in a dual injection locked OEO (DIL-OEO) for ultra low phase noise and minimized spurs.
Photonics Control of Phased Array Antenna/Radar

- Concept / architecture design
- Fiber-based true-time delay beamformer demo
- Semiconductor integrated photonic subsystem
Electronic beamformer array:
- independent control of \((N \times M)\) phase parameters
- frequency dependent phase delay

Photonic True-Time-Delay beamformer array:
- independent control of 2 parameters (for x, y-direction)
- frequency independent true-time delay
- multiple beams/frequencies

For \(N \times M\) 2D array:

\[
\begin{align*}
\text{Tunable Laser} & \quad \text{SSB Modulator} & \quad \text{EDFA} \\
\text{RF in} & \quad & \\
1 \times 2 & \quad \Delta t & \quad t + N \times 2\Delta T_{\text{max}} \\
1 \times 2 & \quad & \\
1 \times 2 & \quad & \\
1 \times 2 & \quad & \\
fiber grating for tunable time delay & \quad & \\
\text{Fiber optics patch} & \quad (\text{fixed compensation time delay}) & \\
\Delta t & \quad t + 2\Delta t + (N-2) \times 2\Delta T_{\text{max}} & \\
\text{Photodetector} & \quad & \\
\end{align*}
\]

ARL Photonic cascading true time delay beamformer
W. Zhou, US patent #: 7609971
The Nation’s Premier Laboratory for Land Forces

A. Experimental Set Up in Anechoic Chamber:

B. Fiber Based RF-Photonic Phased Array Antenna

C. Simulated antenna patterns

C. Experimental Results

Experiment: at 1552.0 nm. Peak Angle: -3°
at 1552.7 nm. Peak Angle: -16°
- Semiconductor integrated photonic beamforming subsystem
ARL (RF-Photonics Team) previous projects demonstrated:

- Fiber Bragg grating based phased array antenna:
- Si-based Slow-light waveguide:

![Group Delay (mm)](image)

- Slow-light waveguide
- Future Integrated Photonic Chip
Analog Time-Correlation Signal Processing

- Concept
- RF Photonic auto-correlation receiver for short pulse spectrum analyze
**Typical RF system’s time limitation:**

For CW RF:

- **Time domain**
  - Received signal: $f_r(\omega t)$
  - Reference (LO): $f_o(\omega_o t)$
  - Super heterodyne

- **Frequency domain**
  - FFT
  - Doppler or modulation

Cannot obtain frequency sideband with one short pulse!

Will not work for ultra-short pulse or fast frequency hopping signal.
Sampling a short pulse is limited by

- **ADC’s speed**
- **Uncertainty principle:** \( \Delta t \Delta f > 1 \)

The maximum observation ("integration") time is \( \Delta t \).
If the observer travels together with the pulse, what is the observation time?
A optical-fiber-recirculation-loop circuit can perform an analog time domain signal correlation processing for a signal with:

- Ultra-wide instantaneous bandwidth
- Ultra-short signal collection time

A Fourier Transformation of the base-band correlation data provide an instant wideband RF spectrum with relative narrow resolution bandwidth:
**True Time-domain Correlation:**

\[
f(t_n) = A^*(t_n) \otimes B(t_n) = \int A^*(t - n \Delta t) B(t) \, dt
\]

\[\Delta t = \tau_1 - \tau_2; \quad t_n = n \Delta t\]

\(n = \text{number of circulations}\)

If \(B = A\), Auto-correlation:

\[A^2 \cos[\omega(n \Delta t) + \varphi]\]

“\(t_n\)” = \(n \Delta t\) to “\(\omega\)” Fourier transfer:

\[F(\omega) = \sum_n f(t_n) \exp(i \omega t_n)\]
Demonstrate <50MHz resolution with two tunes measurements

\[ \Delta f = f_2 - f_1, \quad f_2 = 18\text{GHz} \]

\[ \Delta f = 50\text{MHz} \]

\[ \Delta f = 200\text{MHz} \]

\[ \Delta f = 20\text{MHz} \]
We have developed and demonstrated a new analog RF-photonic time-domain auto-correlation signal processor using an optical fiber recirculation loop circuit:

- Use a single short signal input pulse (~1µs pulse duration).
- 55GHz spectrum bandwidth.
- High resolution (~18mHz) at high frequency.
- Package the system

**Acknowledgement:** Authors thank YY-Labs Inc. for providing technical assistance and packaging.
Thank you!