Electro-optic microdisk
RF receiver

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Outline

- Introduction
- Microwave-photonics
- Microdisk resonant optical modulators
- LiNbO$_3$ microdisk modulator
- LiNbO$_3$ microdisk photonic RF receiver
- Integrated photonic RF receiver
Definitions

- **Optical frequencies** (~ 200 THz)
- **RF and mm-wave frequencies** (5 GHz – 100 GHz)
- **Baseband** (0 – 1 GHz)

**Baseband**
(Digital data, video, voice, …..)

**Data modulated RF carrier** (transmitted carrier)

**RF subcarrier modulated optical carrier**
Conventional and photonic RF receiver architecture

- **Conventional electronic homodyne receiver architecture**
  - High-speed electronics
  - Local oscillator at carrier frequency \( f_{RF} \)
  - Low-noise amplifier
  - RF mixer
  - RF filters

- **Photonic RF receiver architecture**
  - Photonic components
    - Microdisk optical modulator
    - Optical filter
    - Low power DFB laser
    - Low-speed photoreceiver
  - No high-speed electronics
  - No conventional local oscillator
  - No RF mixer
  - Reduced size and power consumption
  - Insensitive to RF carrier frequency
  - Optical isolation

![Diagram of conventional and photonic RF receiver architectures](image)
Applications areas

- **Microdisk photonic RF receiver**
  - Indoor wireless
  - Fiber feed backbone networks
  - Space communication
    - Technology transfer
      - Our 8.7 GHz LiNbO$_3$ microdisk modulator shipped to NASA

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Mars exploration requires new, efficient Ka-band receivers for surface to surface, surface to relay, and surface to Earth communications.
Microwave photonics

- **Microwave-photonics**
  - RF modulation of optical carrier
  - High-speed optical detection
  - Photonic generation of RF signals
  - Photonic RF signal processing

200THz $\approx$ 200GHz

$\nu_1 - \nu_2$
External optical modulator applications:

- **High-speed optical links (10 Gb/s-40 Gb/s)** → broad band Mach-Zehnder modulator
- **mm-wave/RF-optical links**
  - Fabry-Perot modulator (Standing wave)
  - Microdisk modulator (Traveling wave)

Small optical modulator with high sensitivity around a high frequency carrier

**mm-wave/RF optical receiver**

Base band signal

- OD
- OM
- L

$\text{GHz} \quad f$

$\text{GHz} \quad f$

$\text{GHz} \quad f$

$\text{GHz} \quad f$

$\text{GHz} \quad f$

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$\text{GHz} \quad f$
Resonant optical modulators

- **Resonant optical modulator**
  - Long photon lifetime \( \tau_p = Q/\omega_{res} \) ⇒ long interaction length ⇒ high sensitivity
  - Limited modulation bandwidth \( BW \leq \Delta \nu_{FWHM} = \nu_{res}/Q \), centered around integer multiples of the optical free-spectral-range (FSR)

Optical amplitude modulation

--- Traveling wave MZ modulator
— Optically resonant modulator

![Graphs of FSR vs. Disk Diameter](image_url)

- LiNbO₃
- Polymer
- InP, GaAs
Bandwidth and optical quality factor

- **Microdisk modulators**
  - **Semiconductor**
    - InP
    - InGaAsP
  - **Polymer**
    - APC/CPW
    - CLD1/APC
  - **Electro-optic crystals**
    - LiNbO₃
    - SBN
    - KTN

\[
BW \leq \Delta v_{\text{FWHM}} = \frac{v_{\text{res}}}{Q}
\]
**Average size LiNbO₃ microdisk optical resonator**

- Optically polished electro-optic microdisk (LiNbO₃) with curved sidewall for high optical $Q (>10^6)$
  - Measured sidewall roughness
    - Root mean square = 0.846 nm
    - Peak-peak height = 5.1 nm

![Whispering Gallery (WG) modes](image)

Optical power (W)

<table>
<thead>
<tr>
<th>Wavelength (1550.05+...nm)</th>
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<tr>
<td>0</td>
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FSR: 7 – 22 GHz

Diameter = 2.82 mm

Thickness = 0.4 mm

Interferometric surface profiler
RF-photonic LiNbO$_3$ microdisk technology

- **LiNbO$_3$ microdisk modulator**
  - Small volume: $3 \, \text{mm}^3 = \pi \times 3 \times 0.4 \, \text{mm}^3$
  - Large electro-optical coefficient
    $(r_{33} = 30.8 \times 10^{-12} \, \text{m/V})$
  - High-$Q$ optical whispering-gallery (WG) resonance:
    $2 \times 10^6$ - $6 \times 10^6$ (loaded), $1.2 \times 10^7$ (unloaded)
  - Long photon life time:
    1.6 – 5 ns (loaded), 9.5 ns (unloaded)
  - Long interaction length:
    0.2-0.7 m (loaded), 1.3 m (unloaded)
  - High-$Q$ RF resonator:
    $70 – 90$ (loaded), $G_v \propto vQ_{RF}$

- **RF-photonic application**
  - Optical modulation
    - Low power optical amplitude modulation
  - RF signal processing in optical domain
    - High-frequency operation
      - Low loss in optical domain
    - Reduced power consumption
      - Laser diode local oscillator
    - Optical isolation
LiNbO$_3$ microdisk modulator

- **LiNbO$_3$ microdisk modulator**
  - Increased RF sensitivity and low power
    - RF and optical signal in *simultaneous* resonance
    - RF resonance provides voltage gain
    - high-$Q$ (> $10^6$ ) whispering gallery(WG) mode provide long RF-photon interaction time
    - photons highly confined at edge allowing high RF-photon spatial overlap
  - Modulation only occurs at $f_{RF} = m \times \Delta \nu_{FSR}$ with a bandwidth of $\Delta \nu = \nu_0/Q$ $(\nu_{FSR}= \text{optical free spectral range, } m : \text{integer})$
RF ring resonator

- Ring resonator controls the $E$-field inside the LiNbO$_3$ disk
  - Proper spatial distribution
  - Synchronizing the RF and the optical waves
    \[ f_{RF} = m \times \Delta v_{FSR} \quad (m = 1, 2, \ldots) \]
  - $E$-field amplification ($\propto \sqrt{Q_{RF}}$)

![E-field intensity distribution in the middle of the disk](Image)

**Fundamental**

![Simulated fundamental RF resonance](Image)

$P_{in} = 1 \text{ W} \quad (V_{pp} = 20 \text{ V})$

**Second-harmonic**

**magnetic coupling**

- $g = 5.13 \text{ mm}$
- $h = 400 \mu\text{m}$
Third harmonic modulation

- Disk diameter = 5.13 mm
- Disk thickness = 0.4 mm
- $\Delta \nu_{FSR} = 8.7$ GHz
- $f_{RF} = 3 \times \Delta \nu_{FSR} = 26.1$ GHz
- Optical $Q = 3.5 \times 10^6$
- Modulation bandwidth $\approx 50$ MHz
14.6 GHz LiNbO$_3$ microdisk modulator

- 14.6 GHz LiNbO$_3$ microdisk modulator
  - 3 mm diameter LiNbO$_3$ microdisk
    - $D = 3$ mm, $h = 400$ $\mu$m
    - $Q = 4 - 8 \times 10^6$, $FSR = 14.6$ GHz
  - Single prism optical coupling
  - Improved RF coupling
    - fine tuning of the
      ring-microstripline coupling
      coefficient: Critical coupling
      with 350 $\mu$m gap.

- Modified E-field distribution
  - cylindrical symmetric E-field distribution
  - enhanced E-field intensity
Linear modulation at 14.6 GHz

- 14.6 GHz LiNbO$_3$ microdisk modulator
  - Disk diameter = 3 mm
  - Disk thickness = 0.4 mm
  - $\Delta f_{FSR} = 14.6$ GHz
  - $f_{RF} = 14.6$ GHz
  - Optical $Q = 4 \times 10^6$
  - Modulation bandwidth $\approx 45$ MHz

![Graph showing modulated optical power at 14.5 GHz vs. Vpp,in (V) with a peak at 0.7 V.](image)

![Diagram of a 3 mm microstrip line with a microprism, output fiber, and LiNbO$_3$ microdisk modulator.](image)

- Microprism
- Output fiber
- Microring resonator
- LiNbO$_3$ microdisk
- Microstrip line
- 3 mm

![Graph showing transmitted optical power vs. Wavelength 1550+… (nm) with a peak at Q = 4×10^6.](image)
Power sensitivity of single-frequency linear modulation at 14.6 GHz

- Linear modulation sensitivity
  - Dynamic range: > 70 dB
  - SNR of 10 dB at -70 dBm (100 pW)
    - SNR = 1 at -85 dBm RF input power
  - Modulation bandwidth: 80 MHz
  - 0 dBm RF saturation power
  - Fiber-to-Fiber insertion loss ~ 10 dB
  - \( V_{\text{HMM}} \sim 0.4 \) V

![Graph showing the relationship between input RF power and demodulated RF power.](image)

- SNR of 10 dB at -70 dBm (100 pW)
  - SNR = 1 at -85 dBm RF input power

![Graph showing the relationship between wavelength detuning and detected RF power.](image)

- Modulation bandwidth: 80 MHz

![Graph showing the relationship between RF frequency and transmitted optical power.](image)

- 0 dBm RF saturation power
- Fiber-to-Fiber insertion loss ~ 10 dB

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Self-homodyne RF-photonic receiver

- Transmitted carrier RF format
  - Nonlinear mixing of carrier and sidebands in the receiver
  - No local oscillator required

- Photonic baseband down-conversion
  - Second-order nonlinear modulation with optical transfer function ($P_o \propto V_{RF}^2$)
Linear and nonlinear modulation with microdisk modulator

Received signal: \( V_{RF} = V_0 (1 + m_1 \cos(\omega_b)) \cos(\omega_{RF}) \)

Small signal regime \((V_0 < 0.1 V_{HMM})\) and \(\lambda_{ls} = \lambda_{res} : \)

\[
P_o (V_{RF}) = N_0 + \frac{1}{2} N_2 V_{RF}^2 + ...
\]

\[
N_2 = \left. \frac{d^2 P_0}{dV_{RF}^2} \right|_{V_{RF}=0} = f(G_v, Q, P_{o,in}, \kappa, \beta_E, h)
\]

- \(G_v\): voltage gain
- \(Q\): optical Q-factor
- \(P_{o,in}\): input optical power
- \(\beta_E\): E-field correction factor
- \(h\): disk thickness
- \(\kappa\): optical coupling factor
- \(R\): photodetector responsivity

\[
I(V_{RF}) = R P_o (V_{RF}) = R (N_0 + \frac{\gamma}{2} N_2 V_{RF}^2)
\]

\[
I_{\omega_b} \approx R \frac{m_1}{2} N_2 V_{RF}^2
\]

- \(2\omega_{RF}\)
- \(2\omega_{RF} \pm \omega_b\)
- \(2\omega_{RF} \pm 2\omega_b\)

Optical transfer function

Linear output

Nonlinear output

Linear \((P_o \propto V_{RF})\)

Nonlinear \((P_o \propto V_{RF}^2)\)
Critical optical coupling and second-order nonlinear modulation with microdisk modulator

- Transmission dips
  - Zero DC optical power (at $\lambda_{\text{laser}} = \lambda_{\text{res}}$) with critical coupling
    - reduction of optical noise generated by DC optical power
  - Large second-order nonlinearity

Measured transmitted power

Simulation

Optical input power = 50 µW
Optical coupling factor ($\kappa$) = 0.114
Distributed loss (/cm) = 0.0075 ($Q = 1.2 \times 10^7$)
DC shift = 0.135 pm/V
Voltage gain factor (Volt) = 6

$Q = 3 \times 10^6$

First derivative (/10)
Second derivative (/10)

$\lambda_{\text{laser}} = \lambda_{\text{res}}$

$2V_{\text{HMM}} = 1.24$ Volt

Detected optical power (W)

Critical coupling
Experimental arrangement

- Tunable laser: linewidth < 0.5 MHz, resolution < 0.3 pm
- RF mixer
- Variable attenuator
- RF-filter: BW = 1 GHz, centered at 14.5 GHz
- Tunable laser: $\lambda_{\text{laser}} = 1550$ nm

- Signal generator (LO)
- DC power supply
- Amplifier
- Signal/pattern generator
- Isolator
- Polarizer
- Optical output
- RF input
- Low-speed Photodetector
- Baseband output
- Digital data output
Single tone down-conversion

**RF input signal**
- Carrier frequency = 14.6 GHz
- Baseband frequency = 10 MHz
- Transmitted carrier format

**Photodetector**
- Responsivity: 3 mV/μW
- Bandwidth: 100 MHz

\[
V_{RF} = (1 + m_I \cos(\omega_b)) \cos(\omega_{RF})
\]

Voltage amplitude

**Graphs:**
- Down-converted optical power at 10 MHz (dBm)
- Down-converted optical power at 10 MHz (dBm) vs. Wavelength detuning (pm)
- Suppression ratio (dB electrical) vs. RF modulation index \(m_I\)
- Input RF signal vs. Down-converted signal

\(m_I = 0.7\) \((V_{LO}/V_{BB} = 2.8)\)
Optimizing modulation index for single frequency down-conversion efficiency

- **RF modulation format effect**
  - Total received RF power ≈ -15 dB
  - Transmitted carrier format
    - modulation index $m_I < 2$
  - Optimized modulation index
    - measurement $m_I ≈ 0.7$
    - calculation (square law response) $m_I ≈ 0.8$

Calculated down-conversion efficiency and second-harmonic suppression ratio based on ideal square law response
(Down-conversion efficiency $P_{ob}/P_{om}$ is defined as the ratio of modulated optical power at baseband frequency and the total modulated optical power)

- At small signal regime ($P_{RF} < -10$dBm) a modulation index of $m_I = 0.7$ results in 25% down-conversion efficiency and about 15 dB second-harmonic suppression ratio.

**Conclusion**
- $0.7 < m_I < 0.8$ simultaneously optimizes linearity and efficiency of the conversion
Simulated signal flow in RF-photonic receiver

- **Time and frequency domain simulation**
  - **Input RF signal**
    - carrier frequency: 10 GHz
    - baseband signal: 62.5 Mb/s NRZ PRBS data stream.
    - modulation index: 0.6
      
      \[ V_{RF} = (1 + m_I \cos(\omega_b)) \cos(\omega_{RF}) \]
  - Detector band width = 100 MHz
Measured 10 Mb/s data down-conversion from 14.6 GHz carrier

- **Ku-band photonic RF receiver**
  - Carrier frequency: 14.6 GHz
  - Baseband: 10 Mb/s NRZ 2^7-1 PBRS
  - Received RF power measured within 100 MHz bandwidth centered at 14.6 GHz.
  - Digital photo receiver
    - sensitivity: -35 dBm
    - bandwidth: 100 MHz
10 Mb/s, 50 Mb/s and 100 Mb/s data down-conversion from 14.6 GHz carrier

- **Ku-band photonic RF receiver**
  - RF carrier frequency: 14.6 GHz
  - Baseband: 10 Mb/s, 50 Mb/s, 100 Mb/s, NRZ PBRS 2^7-1
  - $m = 0.7$
  - Received RF power: -15 dBm (integrated power measured within 100 MHz bandwidth centered at 14.6 GHz)

![Down-converted eye](image)

Original eye

Time, $t$ (25 ns/div)  

10 Mb/s  

50 Mb/s  

100 Mb/s  

Time, $t$ (10 ns/div)  

Time, $t$ (5 ns/div)
Measurement of 14.6 GHz patch array performance

- 2×2 patch antenna array at 14.6 GHz
  - $\varepsilon_r = 2.94$, $\tan \delta = 0.00119$
  - Efficient and directive radiation
  - Low return loss
  - Planar structure and small size

![Graph showing S11 dB vs. Frequency (GHz) with BW=1 GHz](image)

![Graph showing Received power (dBm) vs. Z (ft)](image)

- Received power at (x = 0, y = 0, R = Z) input power to transmitting antenna = 10 dBm

![Diagram of 22 mm 2×2 patch antenna array at 14.6 GHz](image)

- Efficient and directive radiation
- Low return loss
- Planar structure and small size

![E-plane (y = 0, R = 5.5 ft) and H-plane (x = 0, R = 5.5 ft) plots with power levels -20 dBm, -30 dBm, -40 dBm](image)
14.6 GHz wireless link with microdisk optical receiver

Receiver

Transmitter
Wireless data communication with self-homodyne microdisk optical receiver

- Wireless self-homodyne microdisk RF-photonic receiver
  - 14.6 GHz 4-patch antenna array
  - High sensitivity microdisk optical modulator
  - RF-photonic nonlinear modulation
  - Carrier frequency: 14.6 GHz
  - Modulation index: $m = 0.8$
  - Baseband: 10 Mb/s NRZ PBRS $2^7$-1
  - Input RF power to transmit antenna: 28 dBm

![Image of antenna and modulator setup](image-url)
Future: photonic RF receiver

- **Electrical stabilization and wavelength locking (dc bias on electrodes)**
  - Locking the laser wavelength to a chosen optical transmitted power \( P_{ol} \)

- **Higher carrier frequencies**
  - Harmonic modulation
  - Small disks

![Diagram of photonic RF receiver components including laser, microstrip line, electro-optic microdisk, control circuit, sensitive low-speed photodiode, reference voltage, and optical waveguide.]

![Graph showing detected optical power vs. wavelength with FSR = 340 pm (42.5 GHz) and Q = 1.3×10^6.]

![Image of LiNbO_3 microdisk with dimensions.]

\[ \text{LiNbO}_3 \text{ microdisk} \]

\[ \Delta \lambda_{dc} (0.13 \text{ pm/Volt}) \]

\[ \text{FSR} = 340 \text{ pm} \] (42.5 GHz)
Future: photonic RF receiver

- **Optical filtering**
  - Reduce noise by eliminating the photocurrent from high-frequency components in the signal that are not used.

![Diagram of optical filtering and monolithic integration of photonic RF receiver](image)

- **Monolithic integration of photonic RF receiver**
  - Control circuit
  - Laser
  - Electro-optic microdisk
  - Passive ring resonators
  - Optical waveguide
  - DSP
  - RF signal from antenna
  - Microstripline
  - Data path
Future: microdisk photonic RF receiver integration

- **Electro-optic microdisk modulator for $\lambda = 1550$ nm laser light**
  - **Electro-optic crystals**
    - LiNbO$_3$
      - Electro-optic effect: $r_{33} = 30.8$ pm/V
    - SBN
      - Electro-optic effect: $r_{33} = 246$ pm/V
    - KTN
      - Electro-optic effect: $r_{33} = 600$ pm/V
  - **Polymer (CLD1/APC, APC/CPW)**
    - Electro-optic effect: $r_{33} = 36$-65 pm/V
  - **InP/GaAs**
    - Electro-optic effect: $r_{41} \approx 1.3$-1.4 pm/V
    - Depletion width modulation, electro-absorption (Frank-Keldish effect), ……………….

**Hybrid integration (NASA)**

LiNbO$_3$ mounted on Si optical bench

**Monolithic integration**

Semiconductor or polymer (photonic integrated chip)
Power efficiency

- **60 GHz monolithic electronic receiver (LNA+LO+MX)**
  - 0.15 μm N-AlGaAs/InGaAs HJFET MMIC technology
  - Power consumption = 400 mW
  - Volume: 900 mm³

- **60 GHz photonic receiver**
  - No high-speed electronic devices
  - Less power consumption (<100 mW)
  - Reduced size (< 40 mm³) and complexity
  - Reduced cost

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### Laser
- RIN ≈ -150 dB
- Linewidth ≈ 500 KHz

### Electro-optic microdisk
- $Q \approx 4 \times 10^6$
- Ins. Loss ≈ -10 dB
- $BW < 1 \text{ nm}$
- Slope $> 0.05 \text{ dB/pm}$

### Optical filter
- BER of $10^{-10}$ at –40 dBm
- received optical power

### Baseband output
- Power ≈ 30 mW
- Total power ≈ 130 mW
- Power < 100 mW (CMOS)

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### Power
- Power ≈ 6 mW
- Power ≈ 56 mW
- Power < 50 mW (BiCMOS)

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- Power < 30 dBm, $f_{RF} = 60 \text{ GHz}$
Conclusion

- Microwave photonic technology can provide solutions to current challenges in mm-wave electronic wireless design.

- Nonlinear optical modulation and transmitted carrier RF modulation format may be combined in a self-homodyne architecture to realize a low-power and low-cost photonic RF receiver.

- Microdisk resonant optical modulator is one of the best candidates for self-homodyne photonic RF receiver design.

- Proof of concept experiments with LiNbO₃ microdisk modulator demonstrate the feasibility of electro-optic microdisk wireless receiver for short distance applications.

- By employing alternative electro-optical materials such as semiconductors and polymers, the photonic RF receiver can be integrated in a single chip.
ELECTROMAGNETIC WORLD!
in which DC-to-light is used for communication

- Optical
- Electrical (RF)
- Electrical (baseband)
- Electrical (DC)
RF resonant frequency tuning

- Mechanical tuning of resonant frequency (compatible with MEMS technology)
  - Resonant frequency of the ring resonator can be tuned by varying the height of an air cylinder under the LiNbO$_3$ disk.
  - Accurate tuning of $f_{RF}$ to optical FSR
Feedback loop stabilization

- **Microdisk modulator**
  - LiNbO$_3$ disk ($D = 5.13$ mm, $h = 400$ $\mu$m)
  - RF ring electrode
  - Feedback loop stabilization
    - Tuning the resonant wavelengths by DC voltage.
    - Locking to maximum slope by feedback loop.

![Diagram of LiNbO$_3$ disk modulator](image)

- **High-speed photodetector**
- **Low-speed photodetector**
- **Reference voltage**

![Graph showing detected optical power vs. time](image)

- **RF input**
- **RF output**
- **Laser light in**
- **Laser light out**
- **Splitter**

- **Gold wire**

- **Optical mode spectrum**

- **Wavelength (1550+ nm)**

- **Fed back on**
- **Fed back off**

- **Reference voltage**

- **$\Delta \approx 0.13$ pm/V**
Second harmonic modulation

- Photon in resonance with $E$-field
  - $f_{RF} = 2 \times f_{FSR}$

![Diagram showing RF standing-wave, dielectric microstripline, and ring resonator with RF input and optical traveling wave.](image-url)