# Electro-optic microdisk RF receiver

**Mani Hossein-Zadeh**

**Advanced Network Technology Lab.**
**(www.usc.edu/alevi)**

**4th photonic seminar**
**University of Southern California**

**August 20th , 2004**

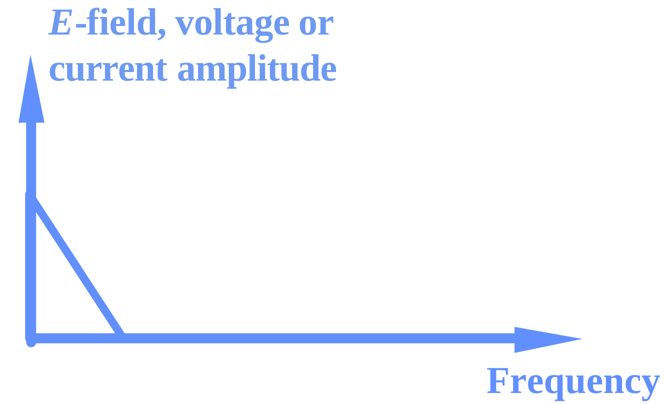
# Outline

- **Introduction**
- **Microwave-photonics**
- **Microdisk resonant optical modulators**
- **$LiNbO_3$ microdisk modulator**
- **$LiNbO_3$ microdisk photonic RF receiver**
- **Integrated photonic RF receiver**

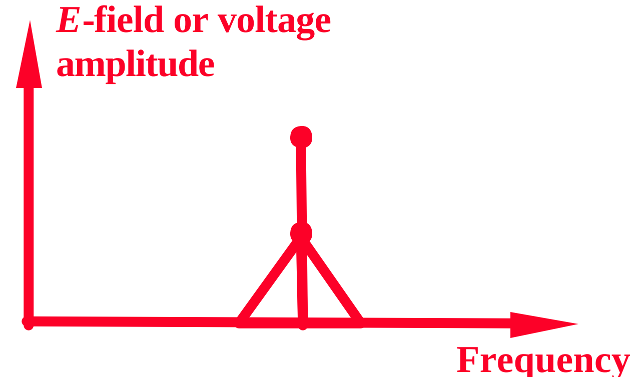
# Definitions

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

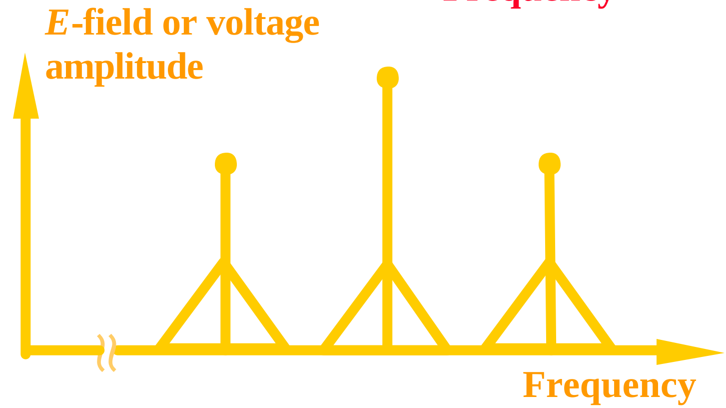
Baseband
(Digital data, video, voice, …..)




Data modulated RF carrier ( transmitted carrier)

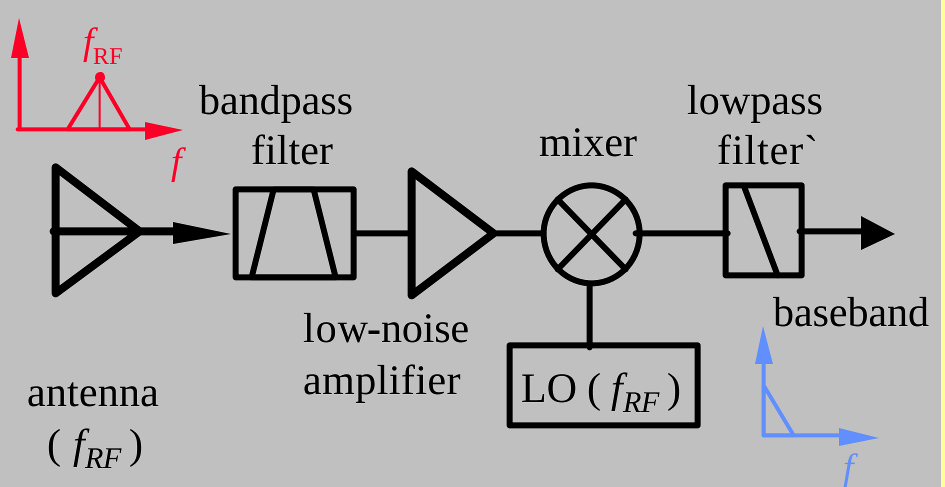



RF subcarrier modulated optical carrier

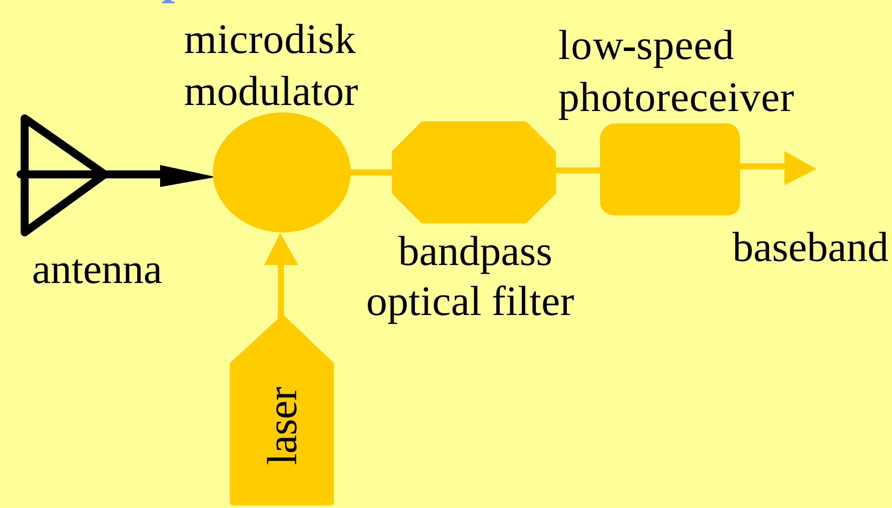


# Conventional and photonic RF receiver architecture

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



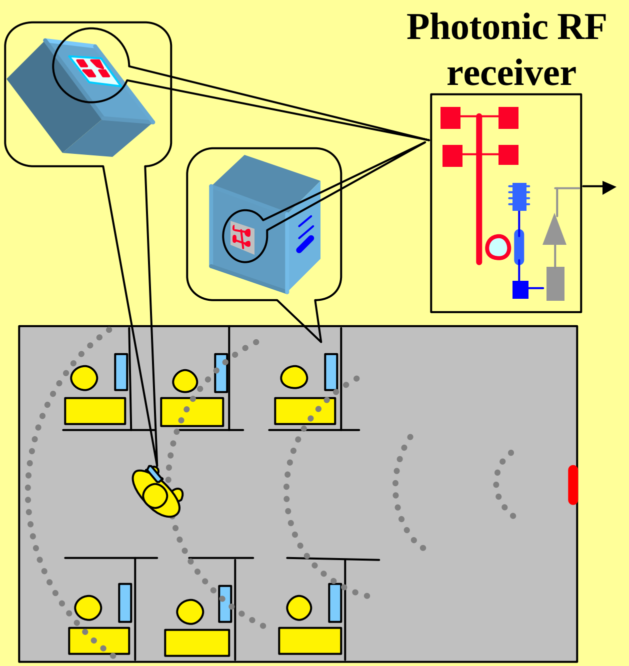

- **Photonic RF receiver architecture**
  - **Photonic components**
    - **Microdisk optical modulator**
    - **Optical filter**
    - **Low power DFB laser**
    - **Low-speed photoreceiver**
  - **No high-speed electronics**
  - **No conventional local oscillator**
  - **No RF mixer**
  - **Reduced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



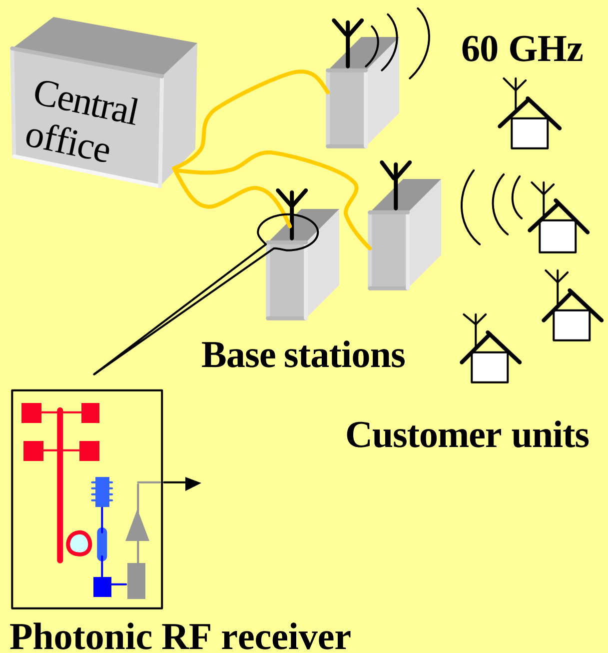
# Applications areas

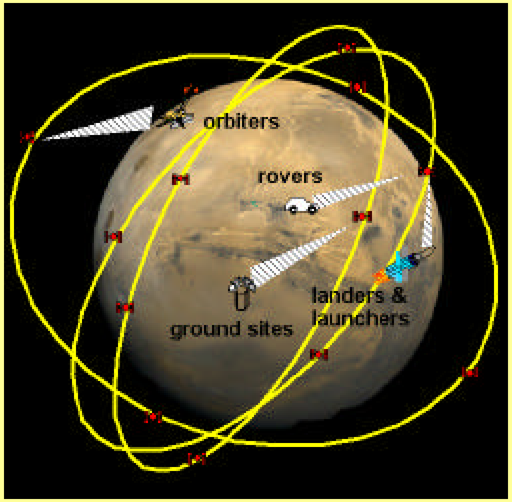
- **Microdisk photonic RF receiver**
  - **Indoor wireless**
  - **Fiber feed backbone networks**
  - **Space communication**
    - **Technology transfer**
      - Our 8.7 GHz $LiNbO_3$ microdisk modulator shipped to NASA

## Indoor wireless LAN




## Fiber feed backbone networks

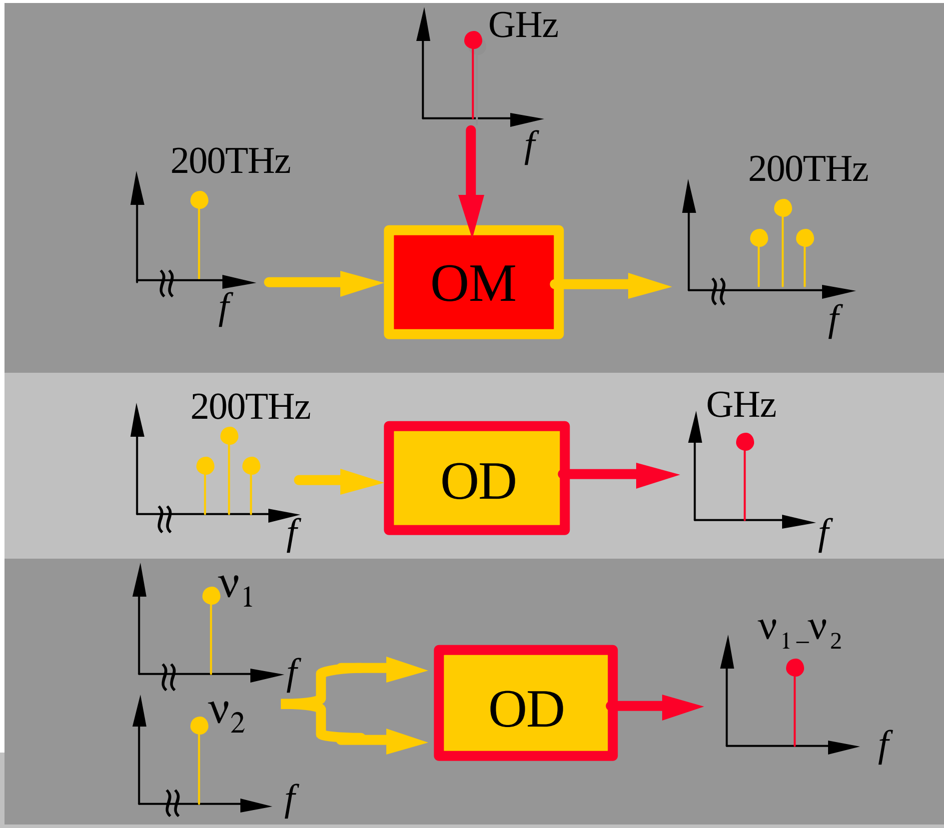


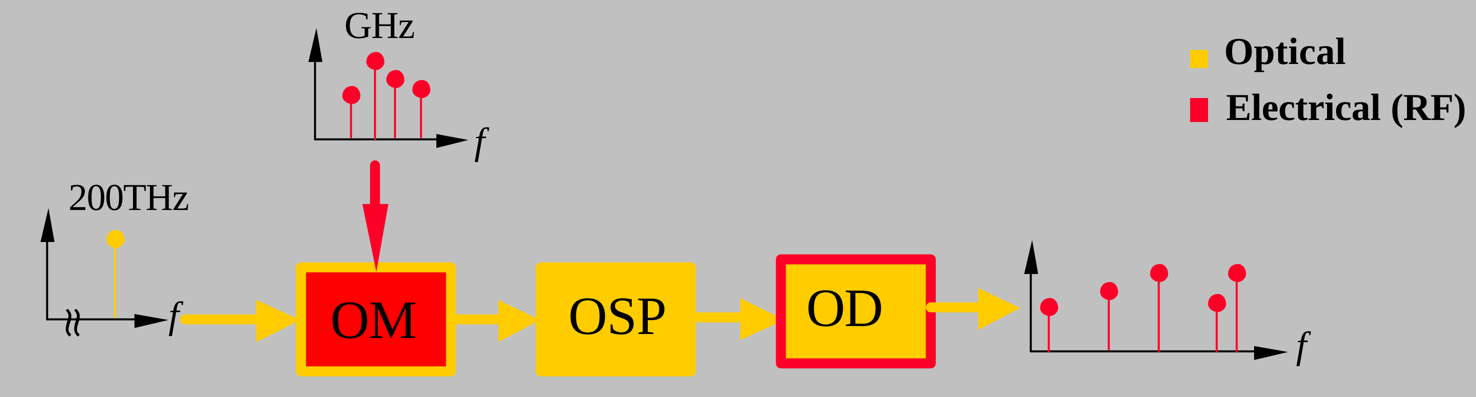




**Mars exploration requires new, efficient Ka-band receivers for surface to surface, surface to relay, and surface to Earth communications.**

# Microwave photonics

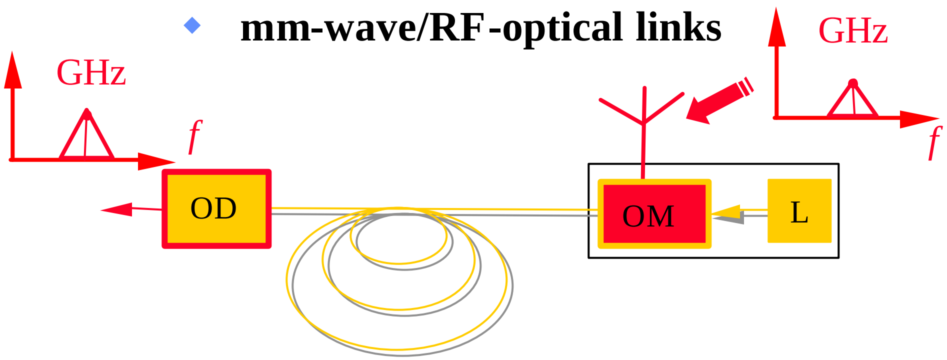
- **Microwave-photonics**
  - **RF modulation of optical carrier**
  - **High-speed optical detection**
  - **Photonic generation of RF signals**
  - **Photonic RF signal processing**



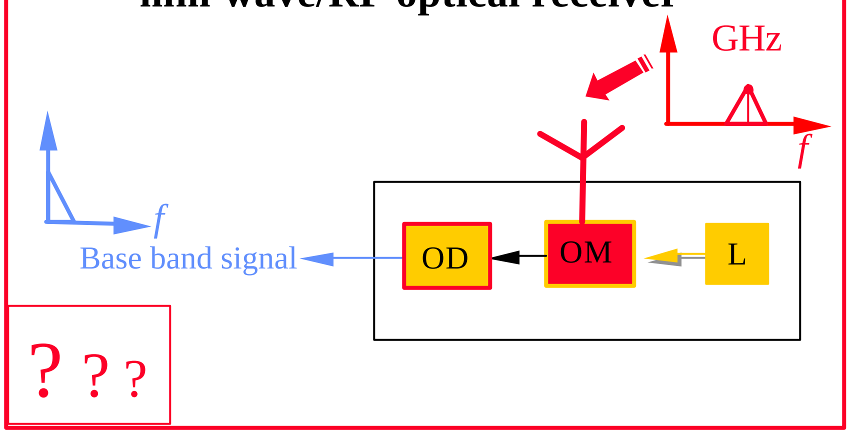



# RF over fiber (RoF)

- **External optical modulator applications:**
  - **High-speed optical links (10 Gb/s-40 Gb/s)** → broad band Mach-Zehnder modulator
  - **mm-wave/RF-optical links**




  - **mm-wave/RF optical receiver**




Small optical modulator with high sensitivity around a high frequency carrier

↓

Resonant modulators

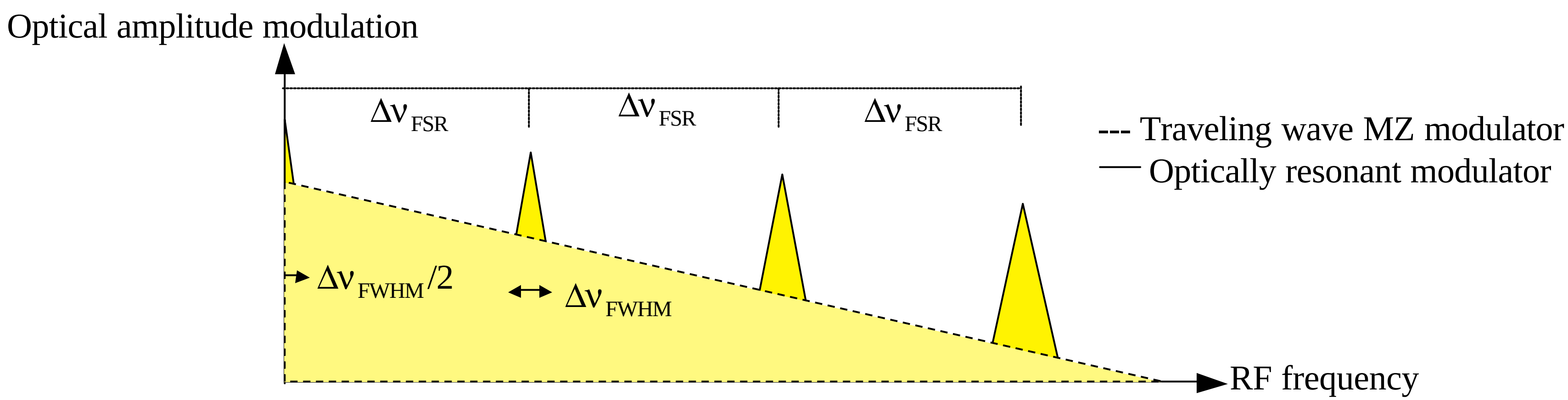
Fabry-Perot modulator (Standing wave)

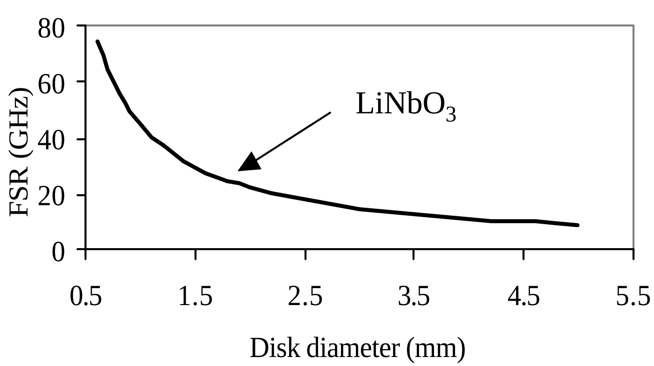
Microdisk modulator (Traveling wave)

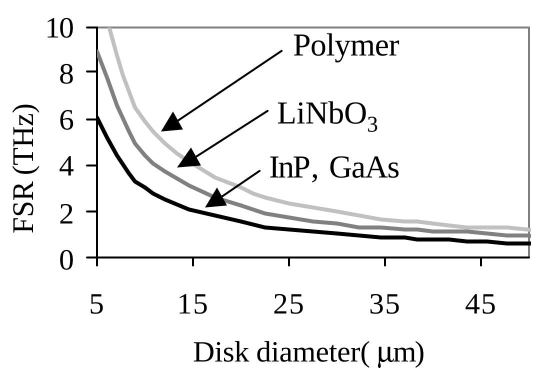
# Resonant optical modulators

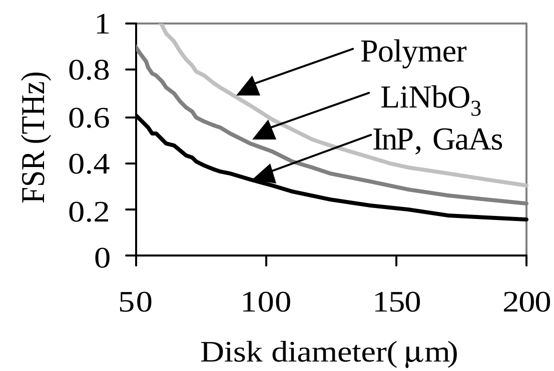
## Resonant optical modulator

- **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)**



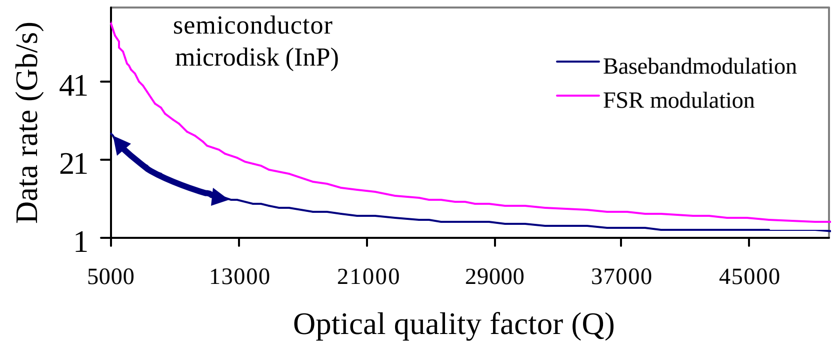



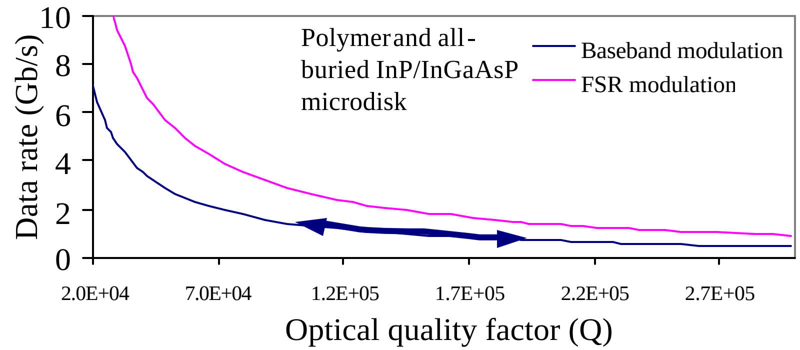



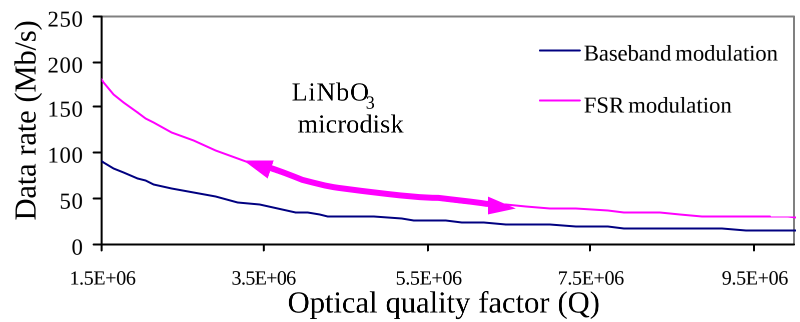
# Bandwidth and optical quality factor

$BW$ £ $Dn_{FWHM} = n_{res} / Q$

- **Microdisk modulators**
  - **Semiconductor**
    - ✧ **InP**
    - ✧ **InGaAsP**
  - **Polymer**
    - ✧ **APC/CPW**
    - ✧ **CLD1/APC**
  - **Electro-optic crystals**
    - ✧ **$LiNbO_3$**
    - ✧ **SBN**
    - ✧ **KTN**



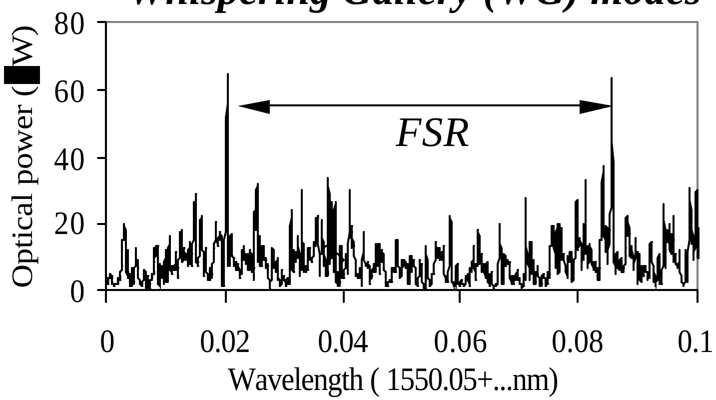



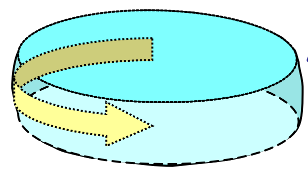



# Average size $LiNbO_3$ microdisk optical resonator

- **Optically polished electro-optic microdisk ($LiNbO_3$) with curved sidewall for high optical *Q* (>$10^6$)**
  - **Measured sidewall roughness**
    - **Root mean square = 0.846 nm**
    - **Peak-peak height = 5.1 nm**

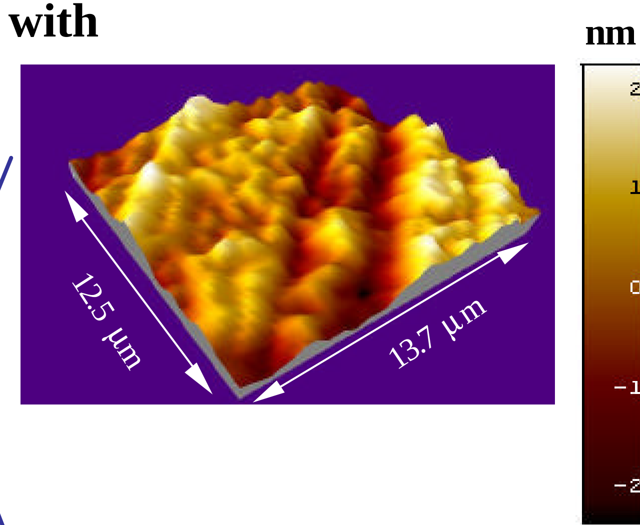
*Whispering Gallery (WG) modes*

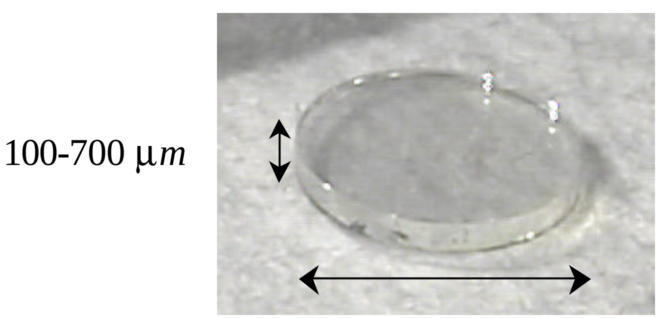


Diameter = 2.82 *mm*

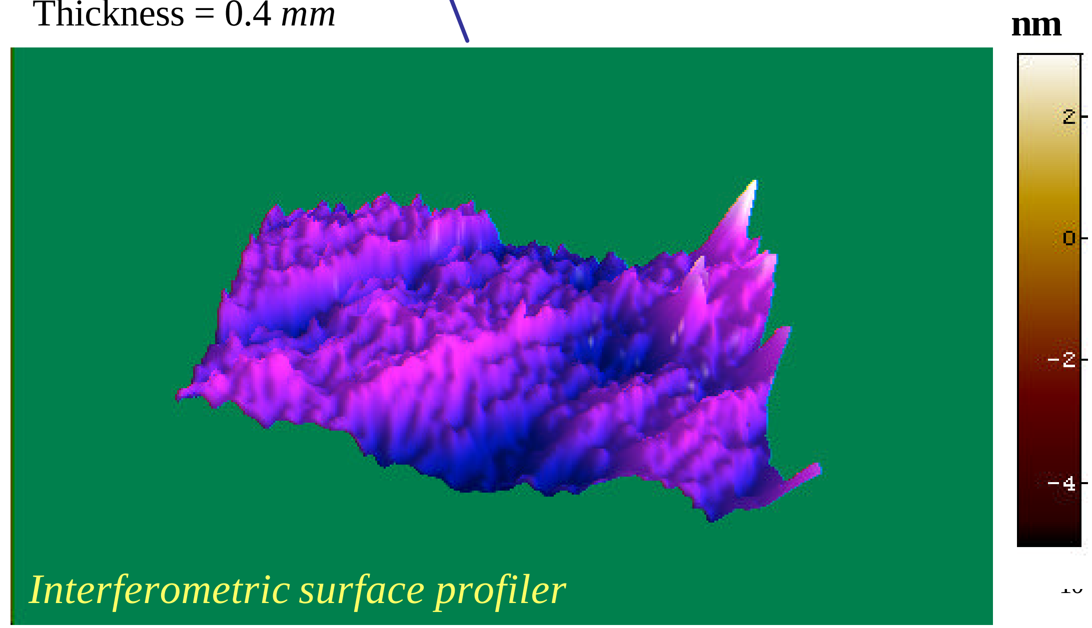
Thickness = 0.4 *mm*




2 - 6 *mm*

FSR: 7 – 22 *GHz*




*Interferometric surface profiler*

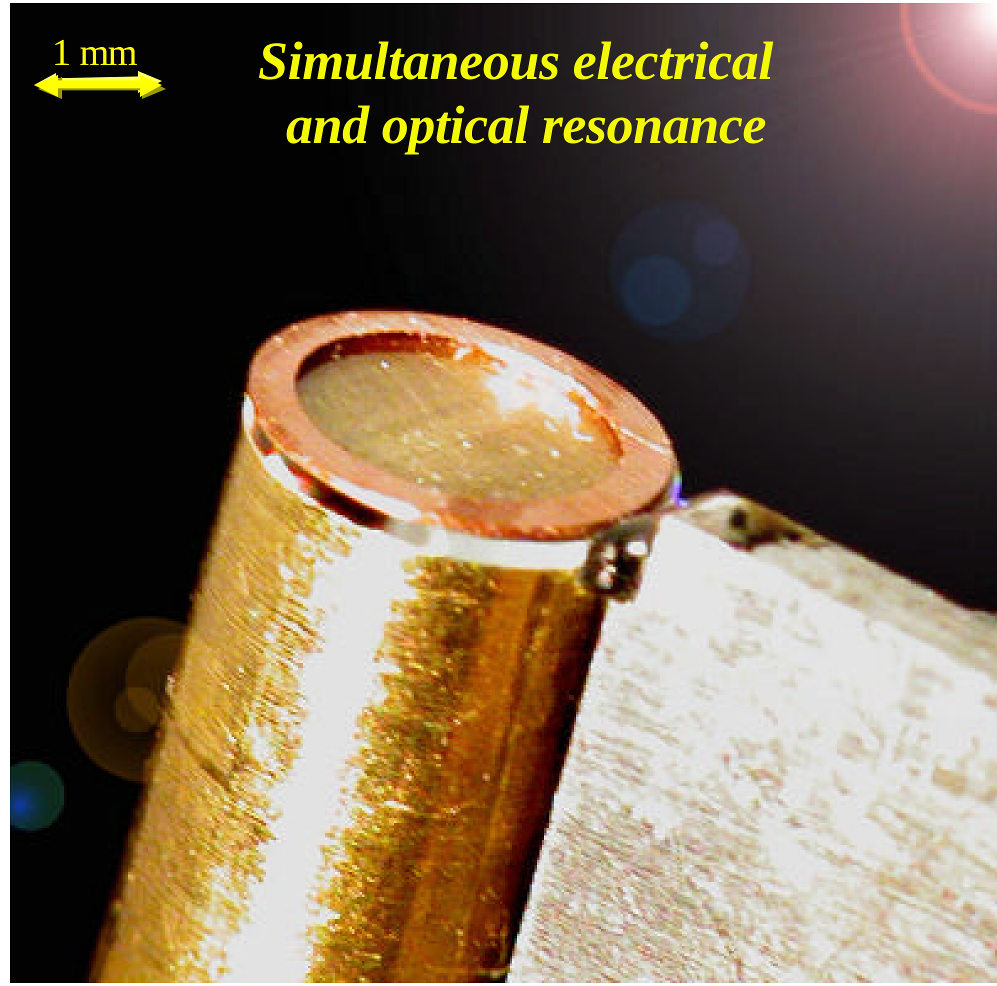
# RF-photonic $LiNbO_3$ microdisk technology

## $LiNbO_3$ microdisk modulator

- **Small volume: 3 mm$^3$ = p$\times$3$\times$0.4 mm$^3$**
- **large electro-optical coefficient**
  ($r_{33} = 30.8\times10^{-12}$ m/V)
- **High-*Q* optical whispering-gallery (WG) resonance:**
  $2\times10^6$- $6\times10^6$ (loaded), $1.2\times10^7$ (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**

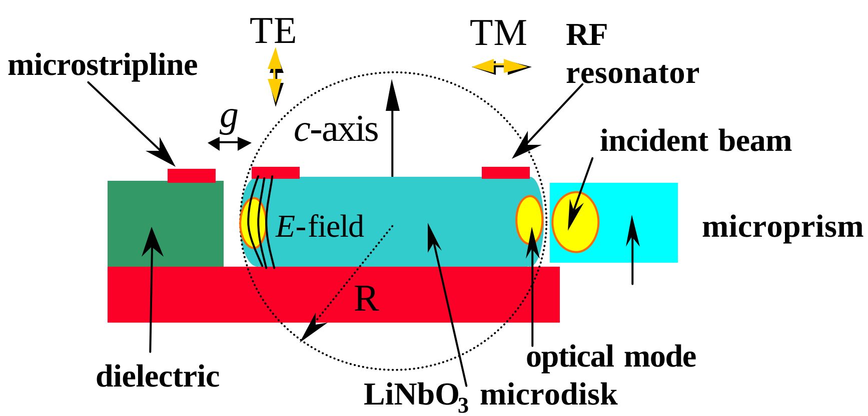


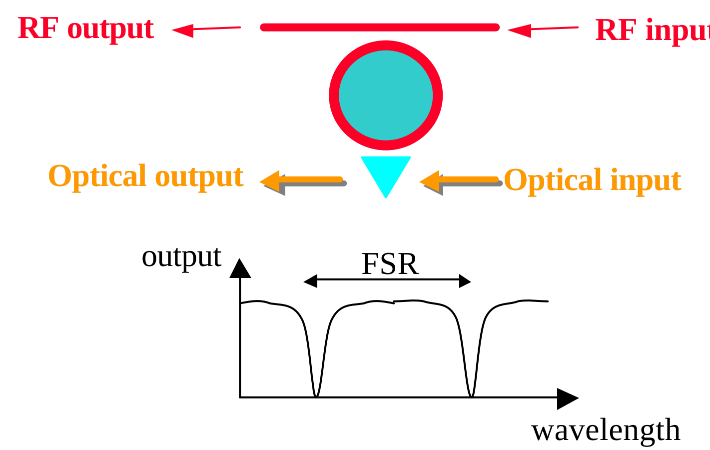

**Combination of *microdisk* and *RF-photonic* technology demonstrated in $LiNbO_3$ microdisk receiver**

# $LiNbO_3$ 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 $f_{RF} = m$ ´ D$n_{FSR}$ with a bandwidth of D$n = n_0/Q$**

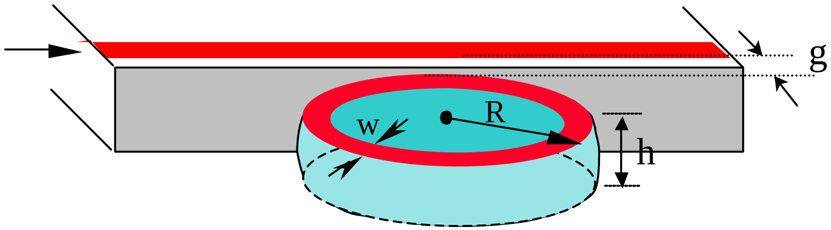
  ($n_{FSR}$= optical free spectral range, *m* : integer)

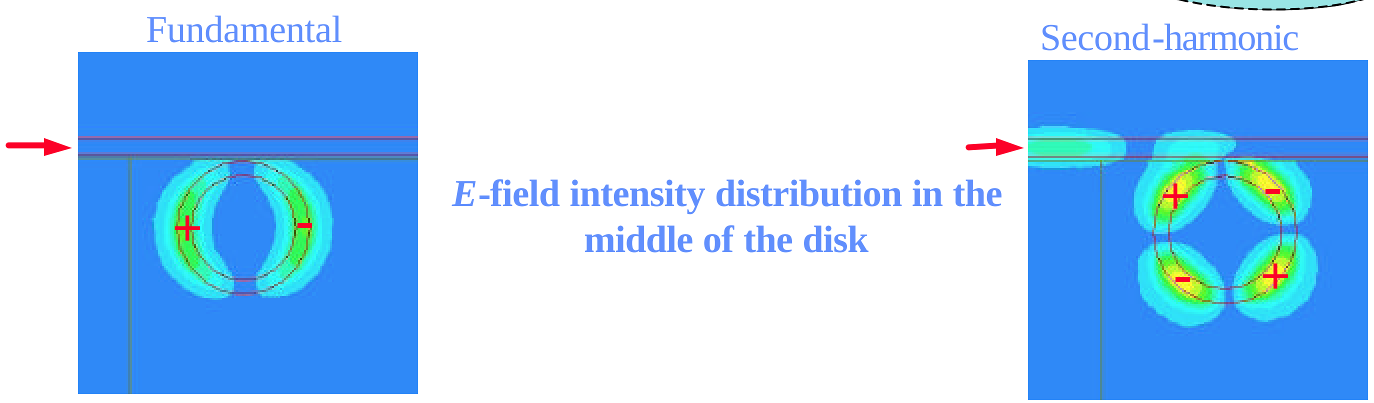


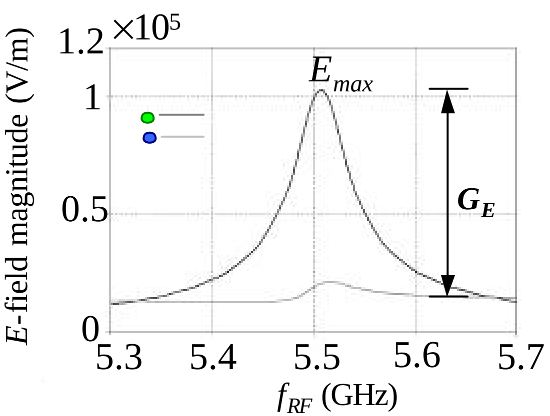
# RF ring resonator

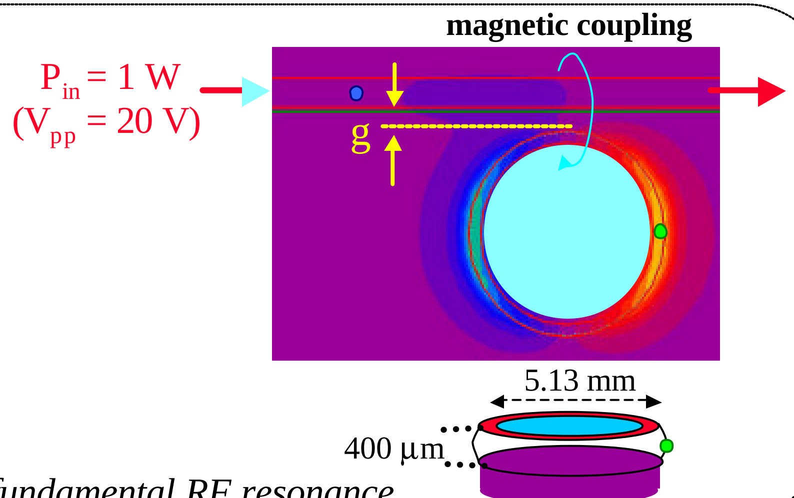
- **Ring resonator controls the *E*-field inside the $LiNbO_3$ disk**
  - **Proper spatial distribution**
  - **Synchronizing the RF and the optical waves**
    - – $f_{RF} = m \times \Delta n_{FSR}$ ($m$ = 1, 2, …)
  - ***E*-field amplification ( µÖ$Q_{RF}$)**




***E*-field intensity distribution in the middle of the disk**



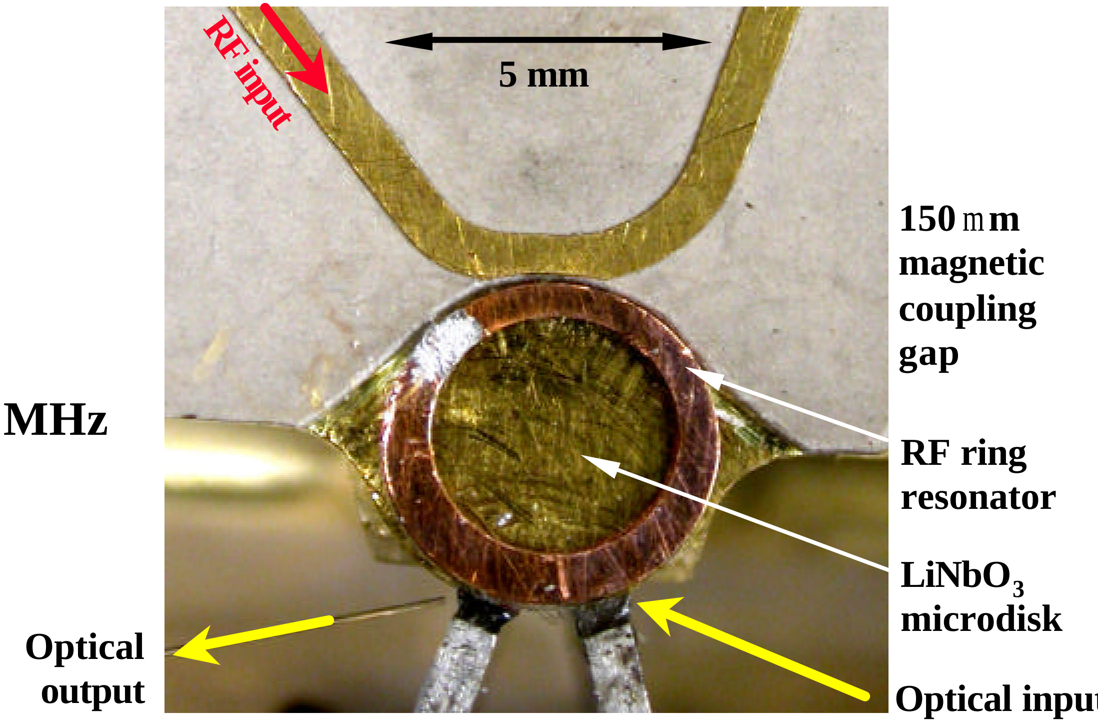



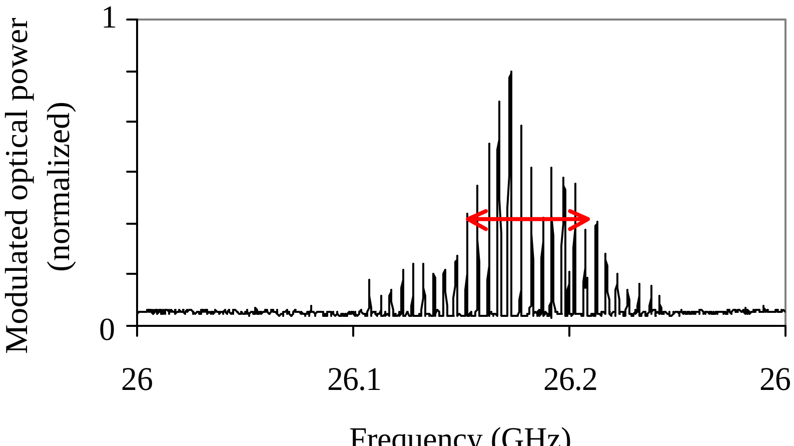

*Simulated fundamental RF resonance*

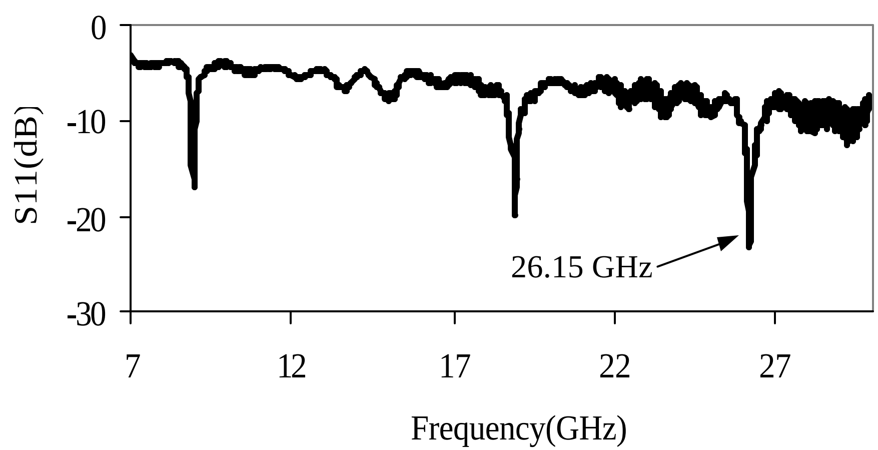
# Third harmonic modulation

## ■ Third harmonic modulation

- Disk diameter = 5.13 *mm*
- Disk thickness = 0.4 *mm*
- $Dn_{FSR}$ = 8.7 GHz
- $f_{RF}$ = 3´ $Dn_{FSR}$ =26.1GHz
- Optical $Q$ = 3.5 ´$10^6$
- Modulation bandwidth » 50 MHz

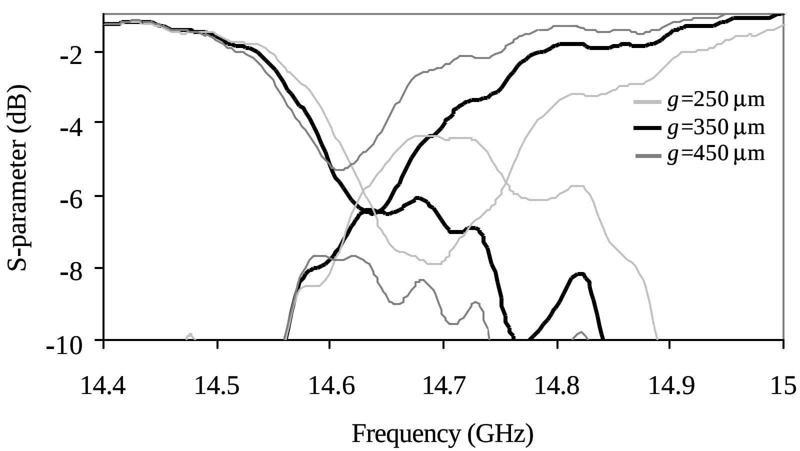


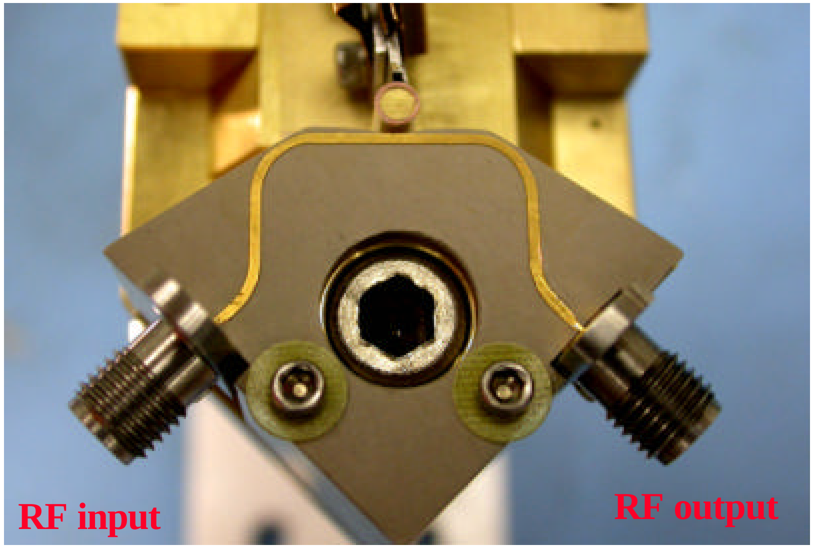



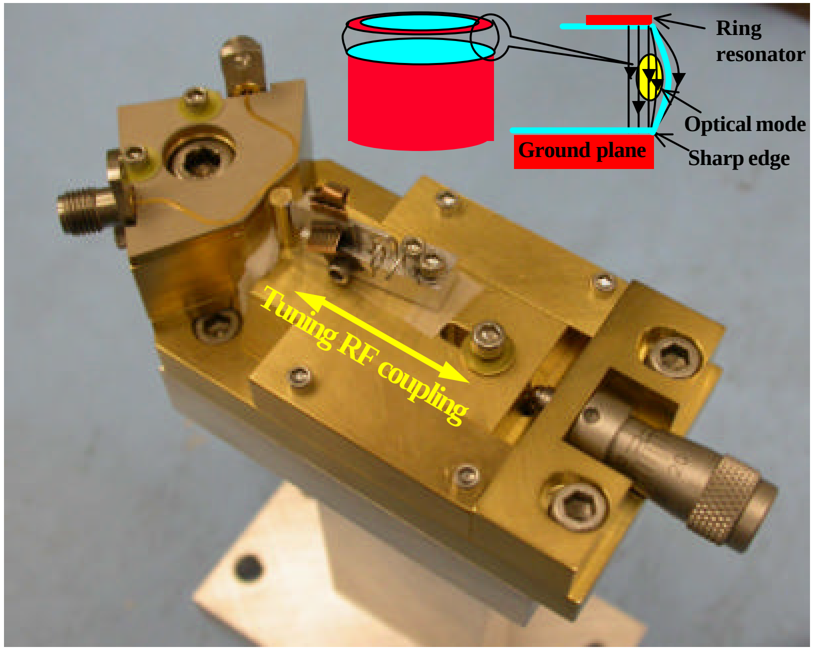



# 14.6 GHz $LiNbO_3$ microdisk modulator

- **14.6 GHz $LiNbO_3$ microdisk modulator**
  - **3 mm diameter $LiNbO_3$ microdisk**
    - ✧ **$D$ = 3 mm, $h$ = 400 μm**
    - ✧ **$Q = 4 – 8 \times 10^6$, $FSR$ = 14.6 GHz**
  - **Single prism optical coupling**
  - **Improved RF coupling**
    - ✧ **fine tuning of the ring-microstripline coupling coefficient: Critical coupling with 350 μm gap.**



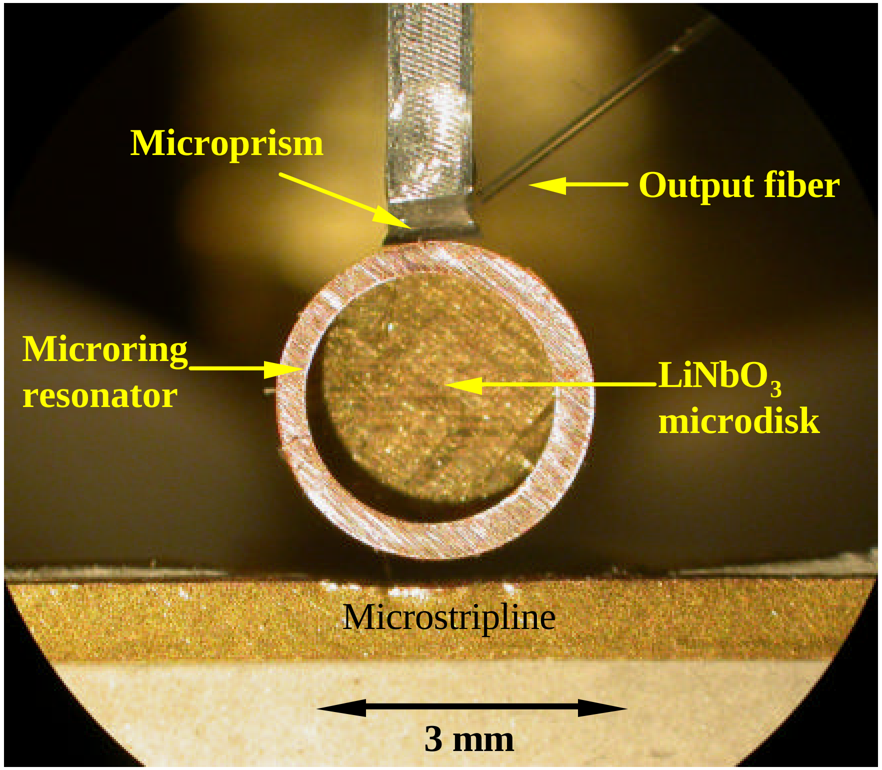



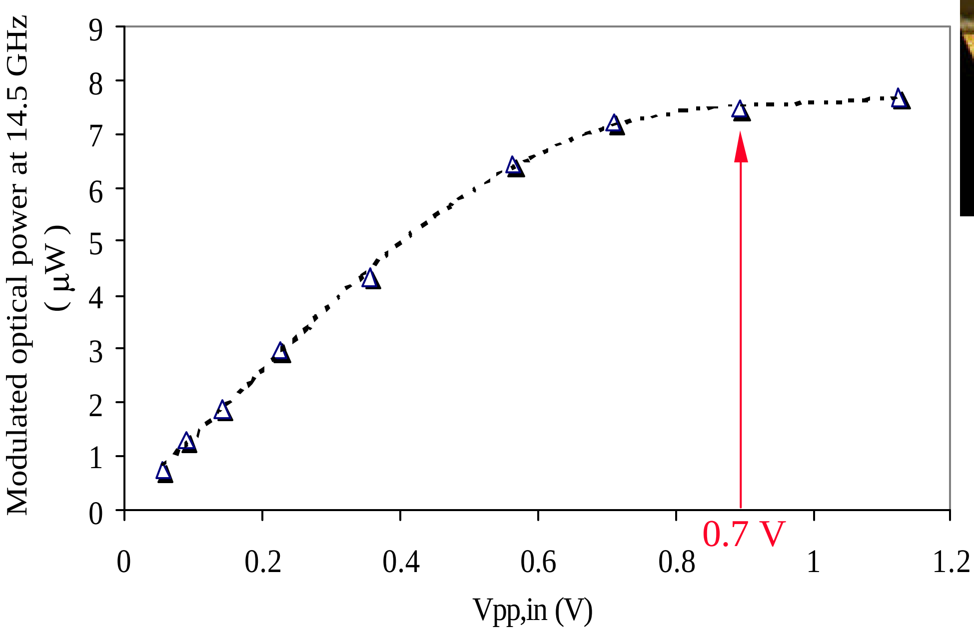



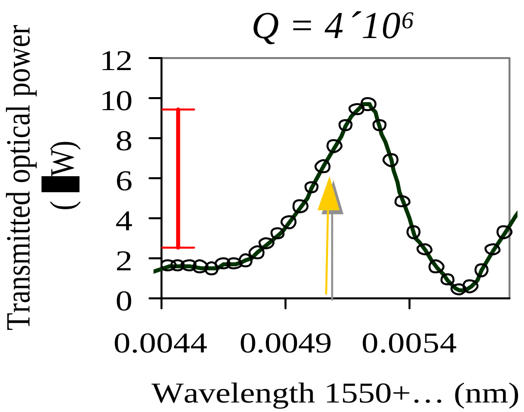

- **Modified E-field distribution**
  - ✧ **cylindrical symmetric *E*-field distribution**
  - ✧ **enhanced *E*-field intensity**

# Linear modulation at 14.6 GHz

- **14.6 GHz $LiNbO_3$ microdisk modulator**
  - **Disk diameter = 3 *mm***
  - **Disk thickness = 0.4 *mm***
  - $Dn_{FSR}$ **= 14.6 GHz**
  - $f_{RF}$ **= 14.6 GHz**
  - **Optical *Q* = 4 ´ $10^6$**
  - **Modulation bandwidth » 45 MHz**

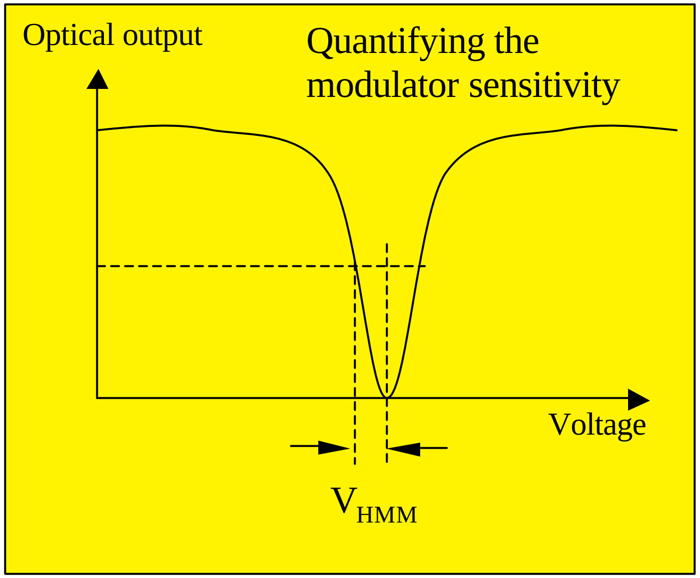


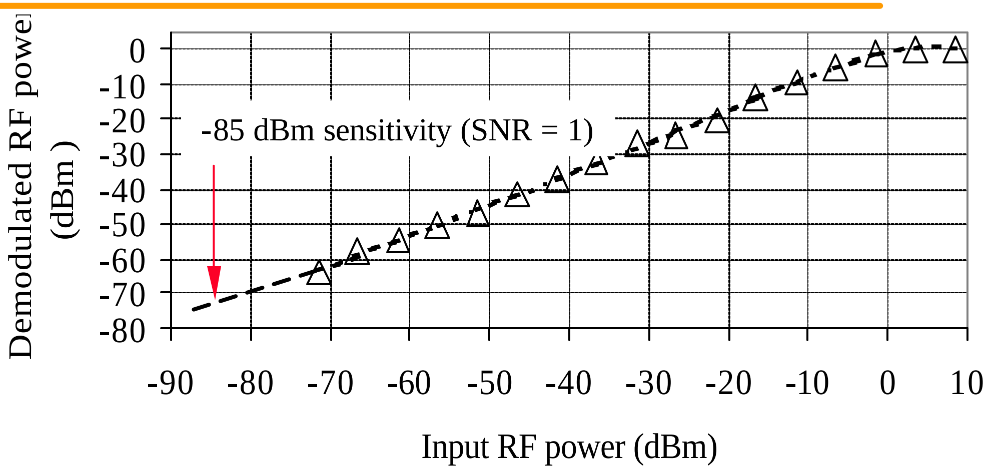



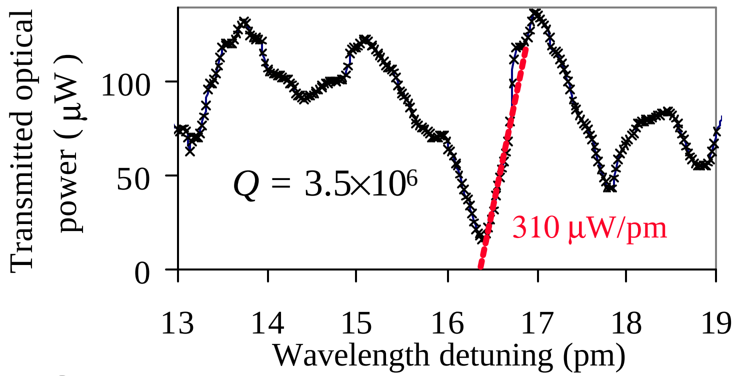



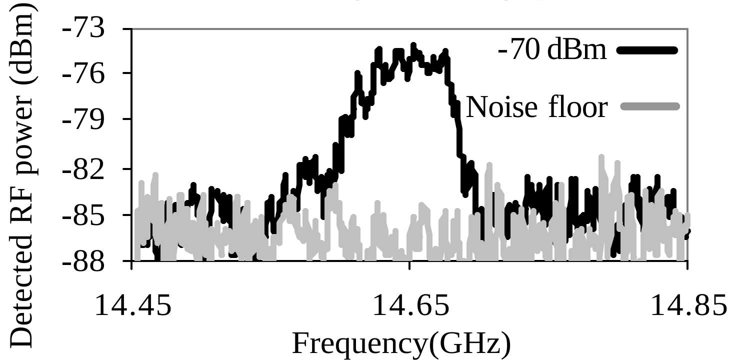
# Power sensitivity of single-frequency linear modulation at 14.6 GHz

- **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**
  - **$V_{HMM}$ ~ 0.4 V**



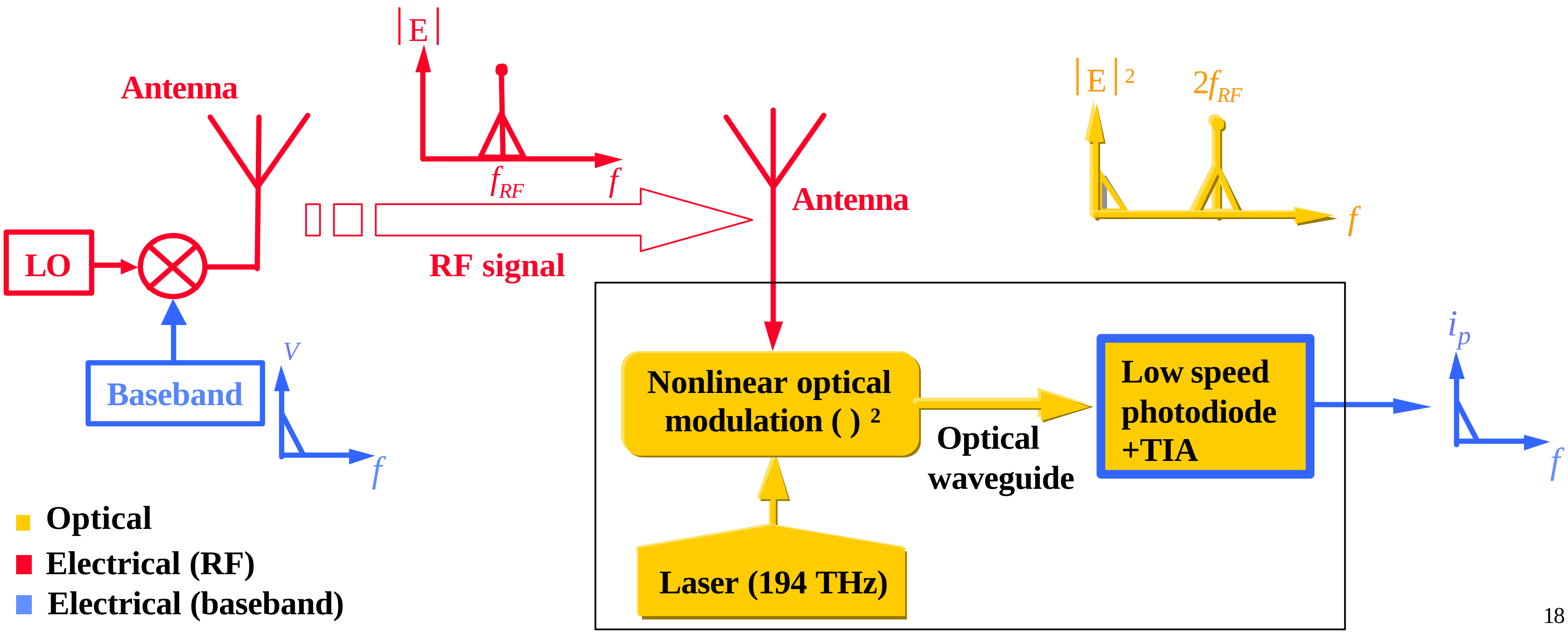



# Self-homodyne RF-photonic receiver

- **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 ($P_o \mu V_{RF}^2$)**




Optical
Electrical (RF)
Electrical (baseband)

# Linear and nonlinear modulation with microdisk modulator

**Received signal:** $V_{RF} = V_0(1 + m_I \cos(w_b))\cos(w_{RF})$

**Small signal regime *($V_0$ < 0.1$V_{HMM}$)* and l $_{las}$ = l $_{res}$ :**

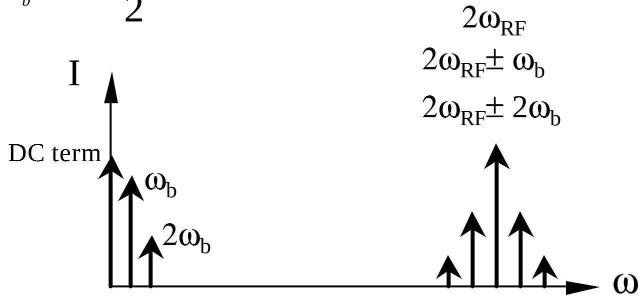
$$P_o(V_{RF}) = N_0 + \frac{1}{2} N_2 V_{RF}^2 + \ldots$$

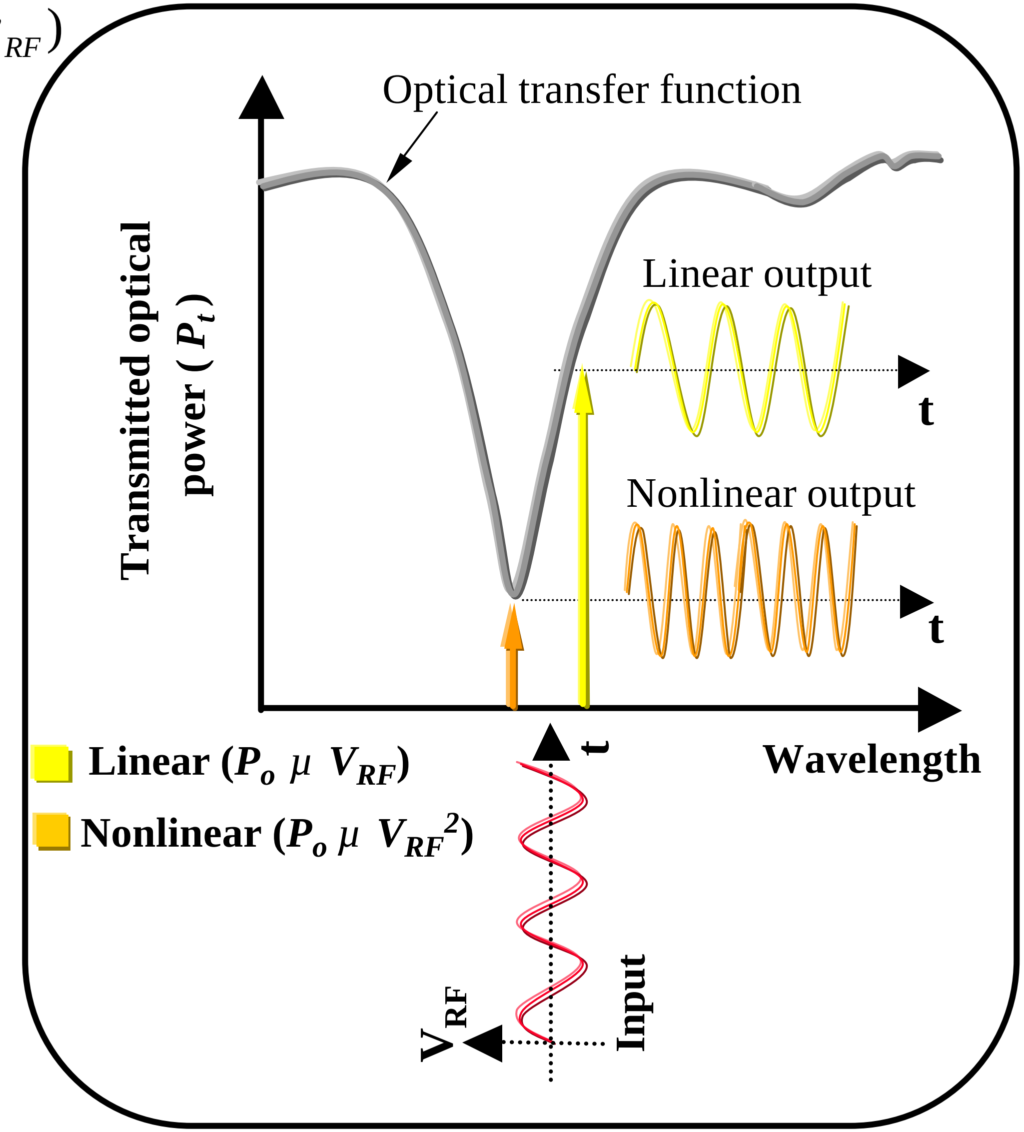
$$N_2 = \left. \frac{d^2 P_0}{dV_{RF}^2} \right|_{V_{RF}=0} = f(G_V, Q, P_{o,in}, k, b_E, h)$$

***$G_V$*: voltage gain**
***Q*: optical Q-factor**
***$P_{o,in}$*: input optical power**
$b_E$**: E-field correction factor**
***h*: disk thickness**
*k*: **optical coupling factor**
***R*: photodetector responsivity**

$$I(V_{RF}) = RP_o(V_{RF}) = R(N_0 + \frac{g}{2} N_2 V_{RF}^2)$$

$$I_{w_b} \approx R \frac{m_I}{2} N_2 V_{RF}^2$$



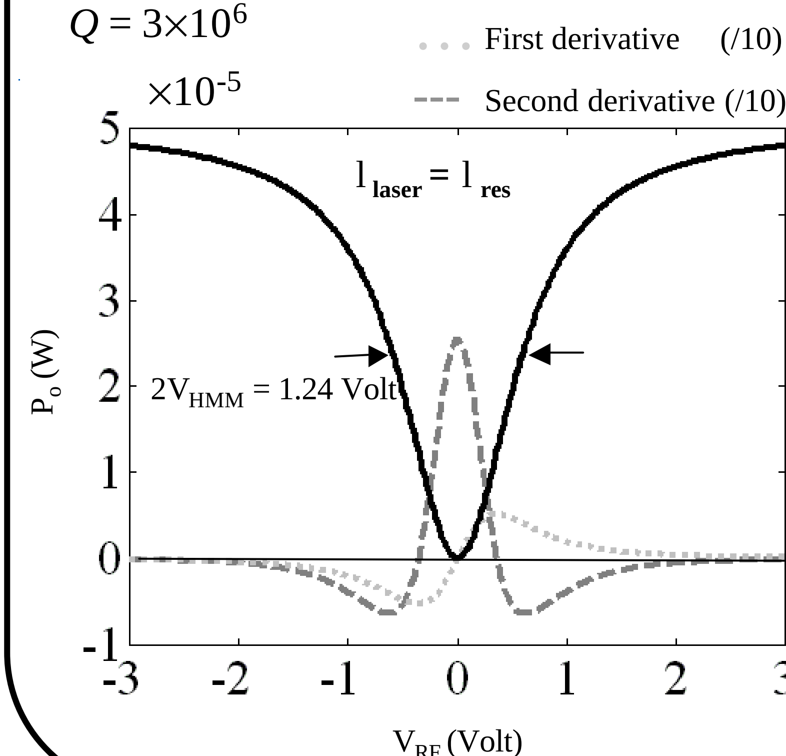



# Critical optical coupling and second-order nonlinear modulation with microdisk modulator

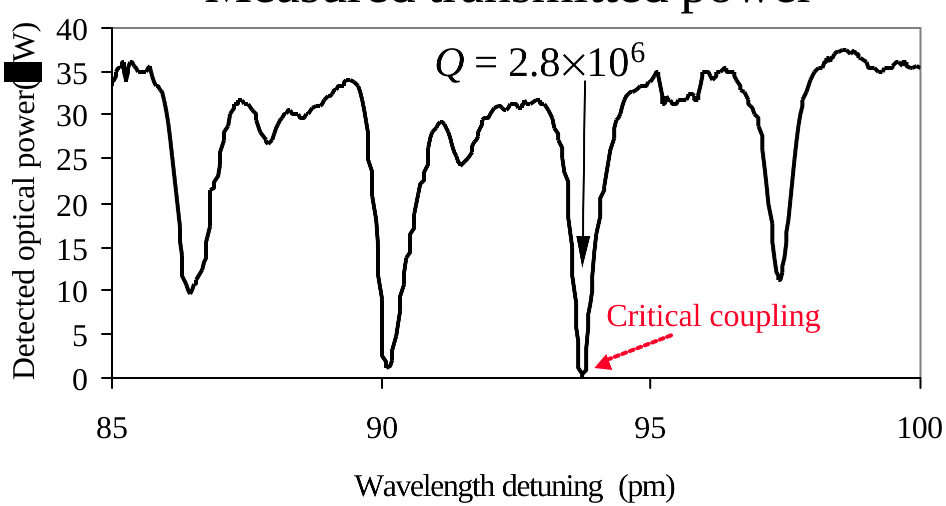
- **Transmission dips**
  - **Zero DC optical power (at $l_{laser} = l_{res}$) with critical coupling**
    - **reduction of optical noise generated by DC optical power**
  - **Large second-order nonlinearity**

## Simulation

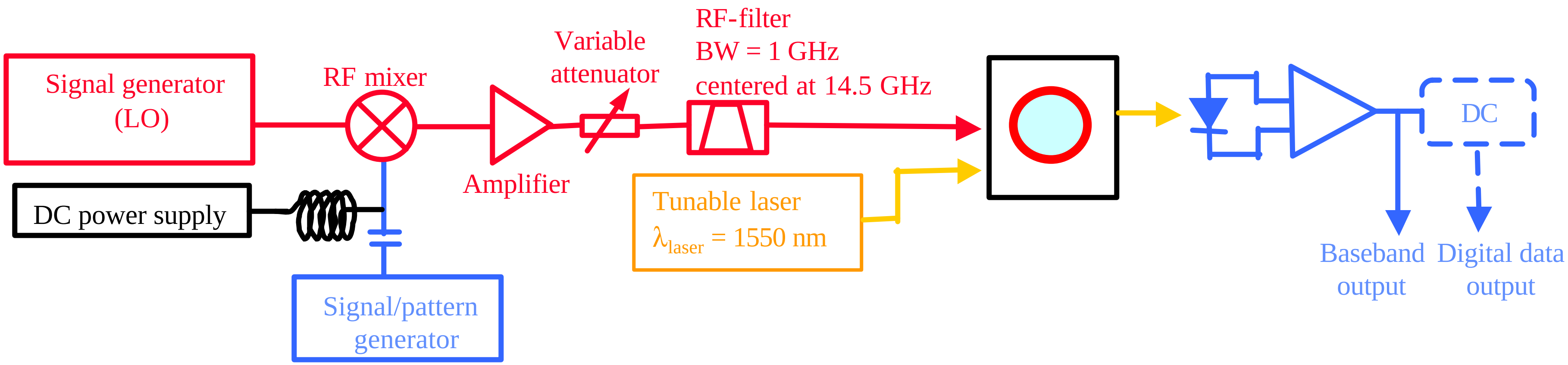
Optical input power = 50 μW
Optical coupling factor (κ)= 0.114
Distributed loss (/cm) = 0.0075 ($Q = 1.2\times10^7$)
DC shift = 0.135 pm/V
Voltage gain factor (Volt) = 6
$Q = 3\times10^6$

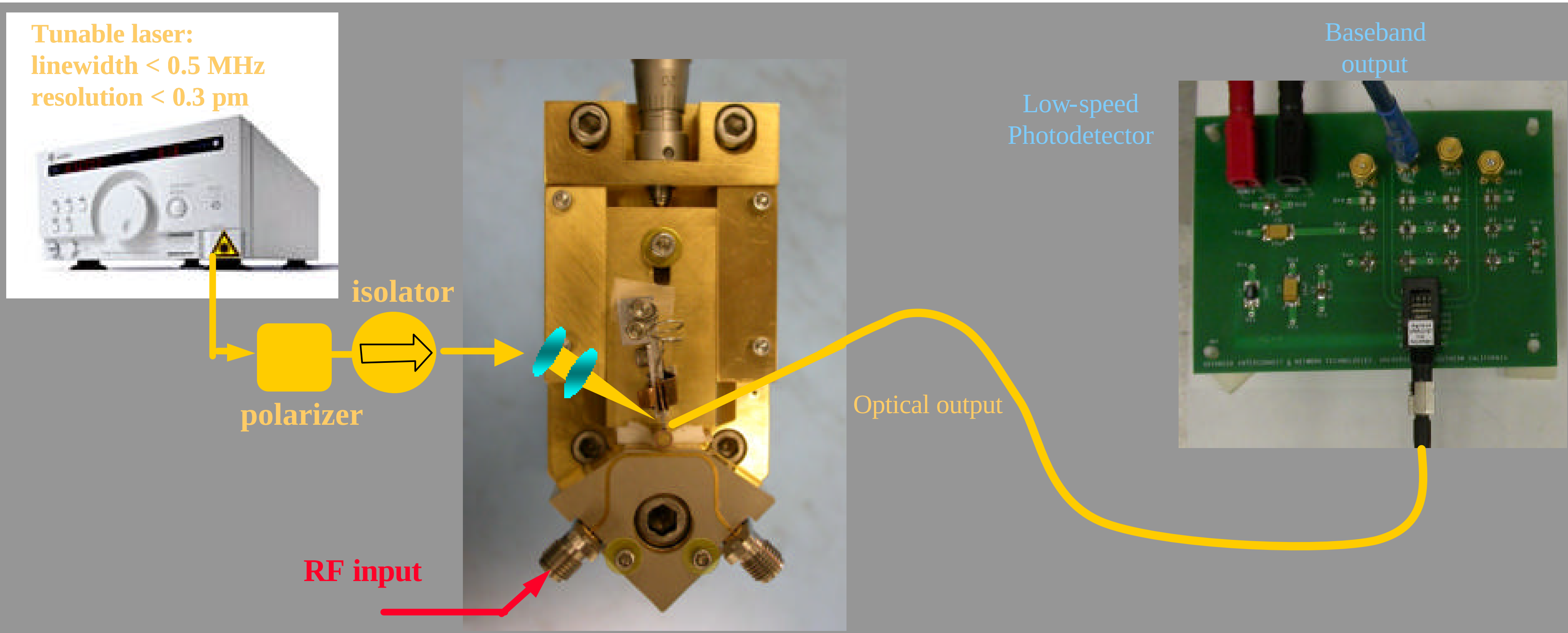



Measured transmitted power



# Experimental arrangement

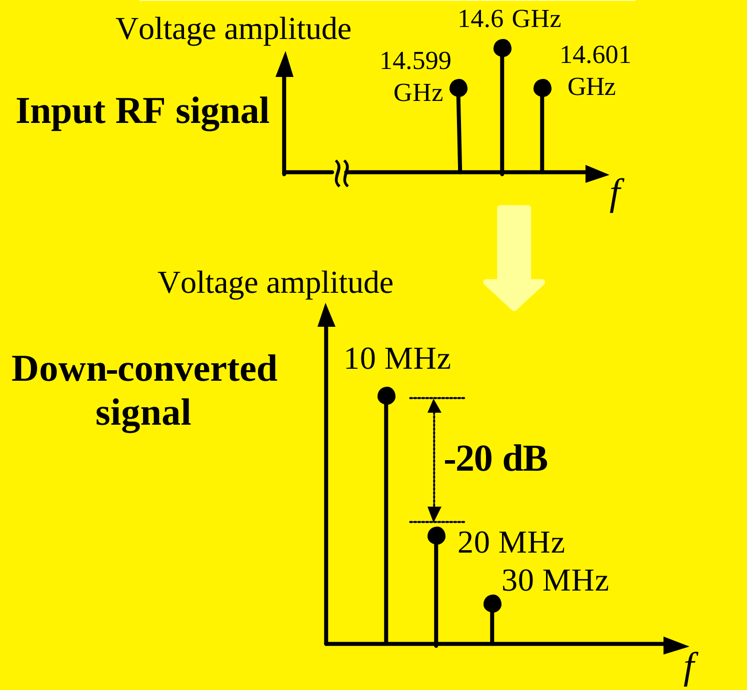


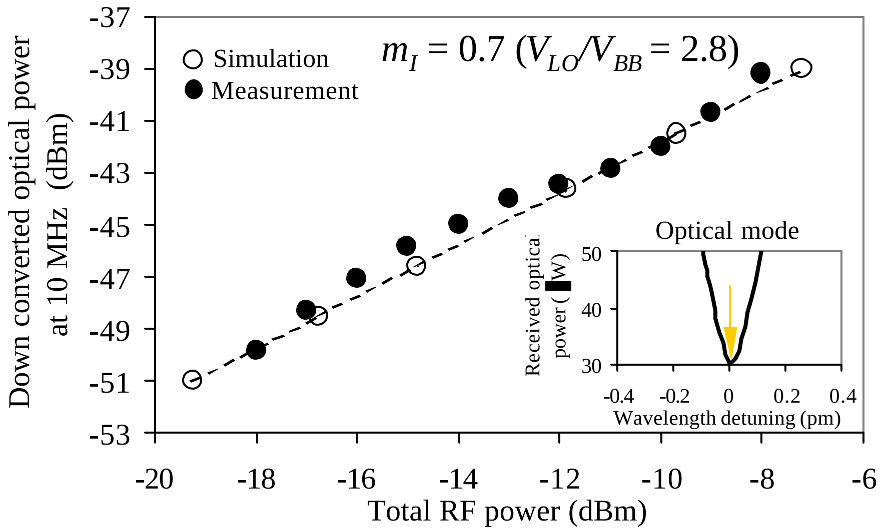



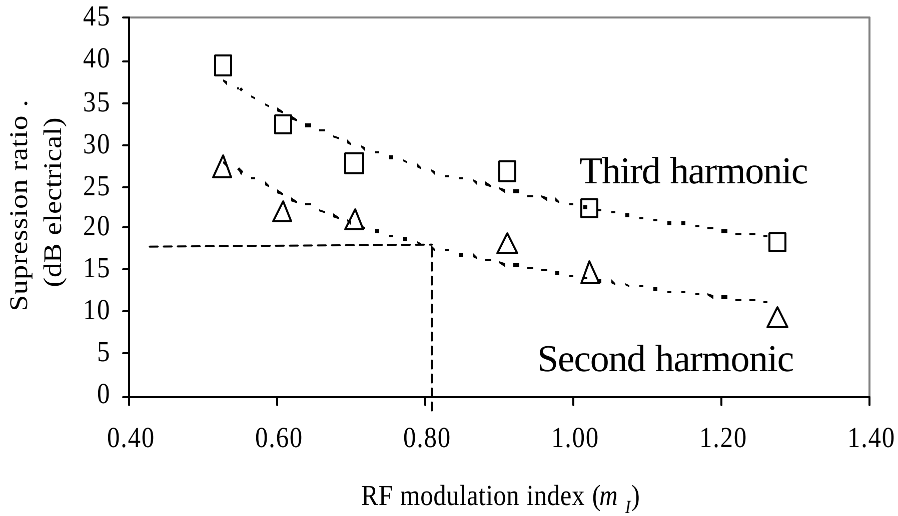
# Single tone down-conversion

- **RF input signal**
  - **Carrier frequency = 14.6 GHz**
  - **Baseband frequency = 10 MHz**
  - **Transmitted carrier format**
- **Photodetector**
  - **Responsivity: 3 mV/mW**
  - **Bandwidth: 100 MHz**

$$V_{RF} = (1 + m_I \cos(w_b)) \cos(w_{RF})$$

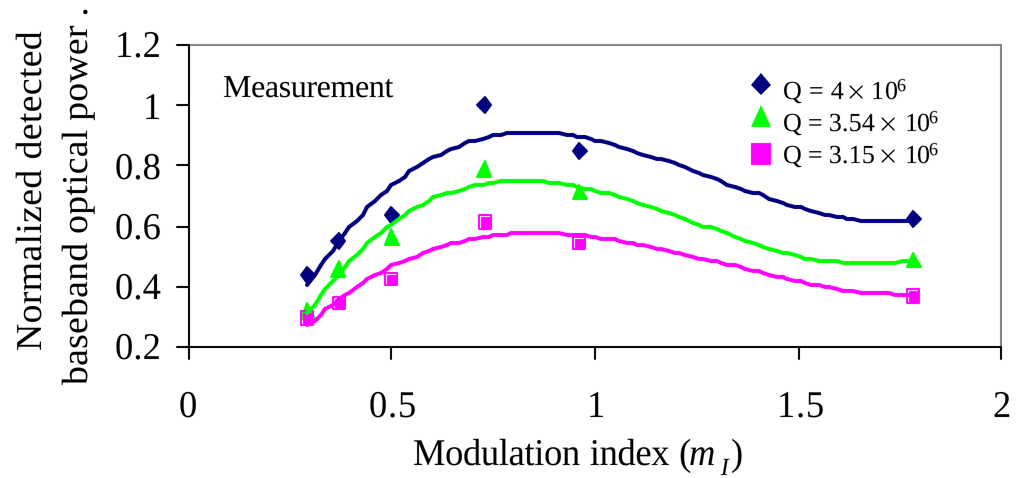


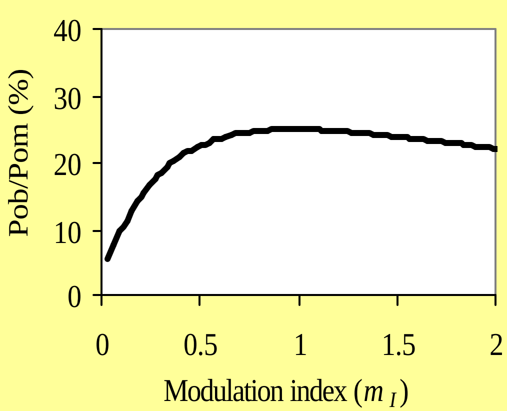
# Optimizing modulation index for single frequency down-conversion efficiency

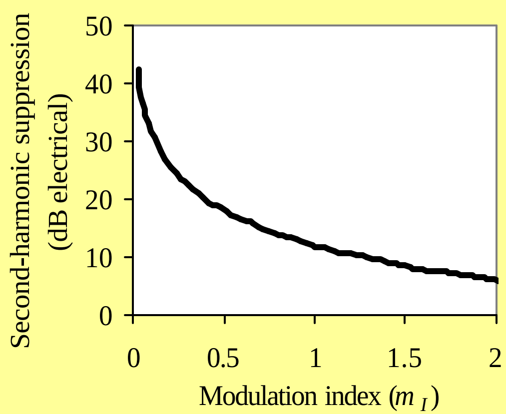
- **RF modulation format effect**
  - **Total received RF power » -15 dB**
  - **Transmitted carrier format**
    - **modulation index $m_I < 2$**
  - **Optimized modulation index**
    - **measurement $m_I$ » 0.7**
    - **calculation (square law response) $m_I$ » 0.8**




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

**Conclusion**

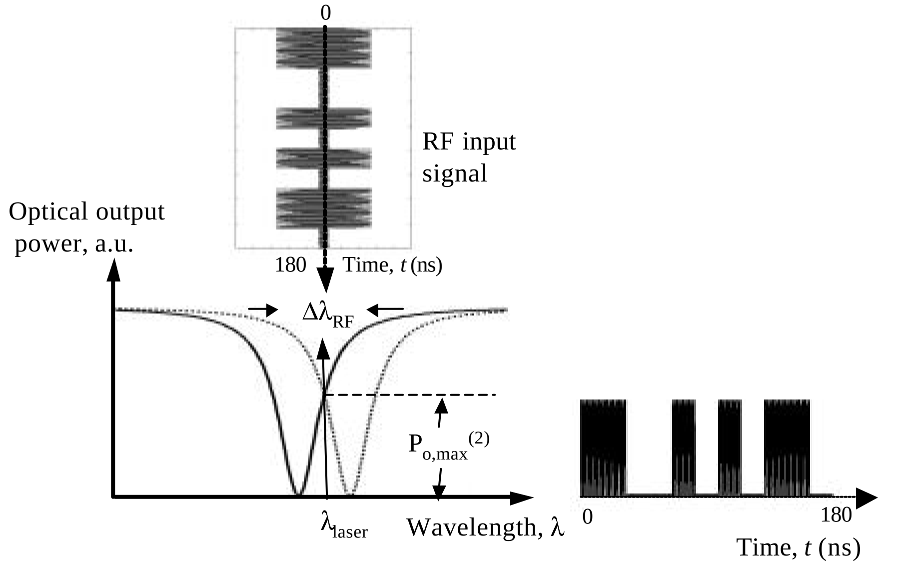
- **0.7< $m_I$ <0.8 simultaneously optimizes linearity and efficiency of the conversion**

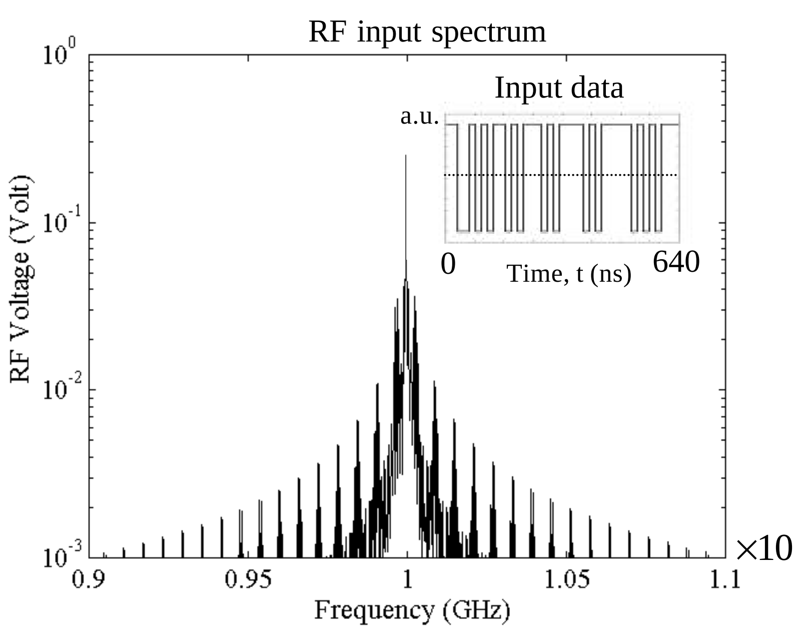
# Simulated signal flow in RF-photonic receiver

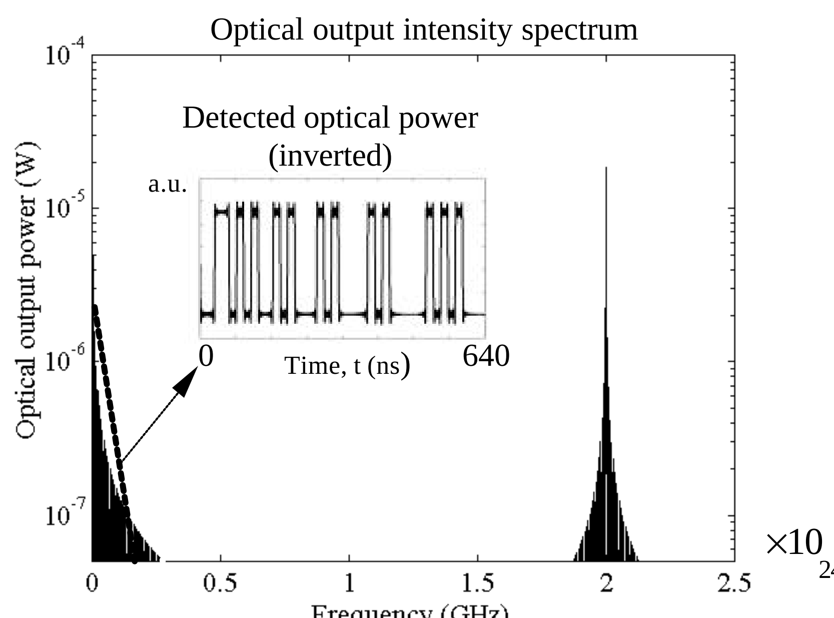
- **Time and frequency domain simulation**
  - **Input RF signal**
    - **carrier frequency : 10 GHz**
    - **baseband signal : 62.5 Mb/s NRZ PRBS data stream.**
    - **modulation index : 0.6**

$$V_{RF} = (1 + m_I \cos(w_b))\cos(w_{RF})$$

  - **Detector band width = 100 MHz**

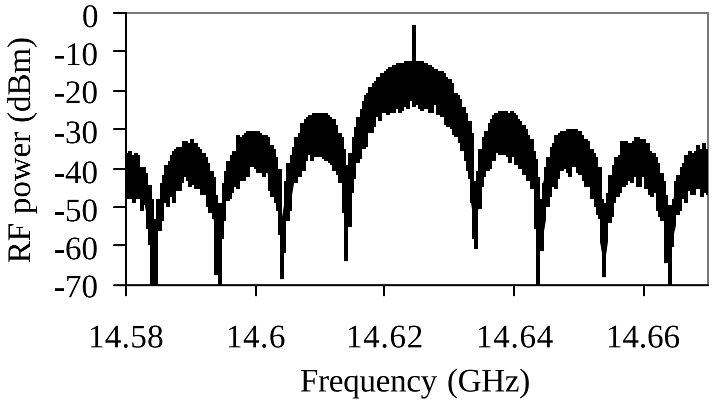


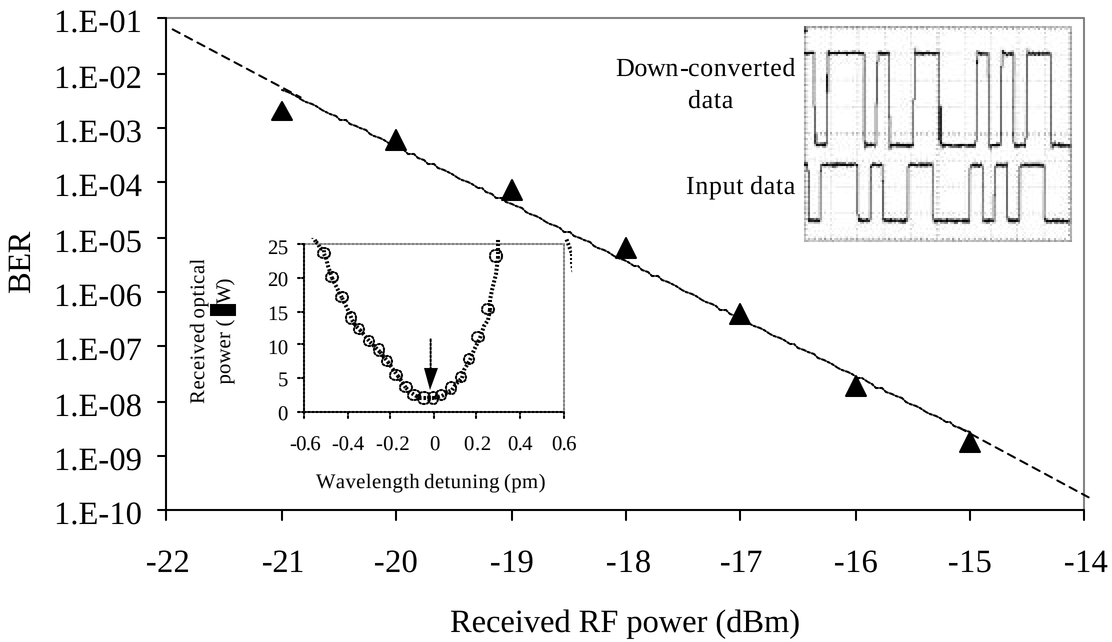



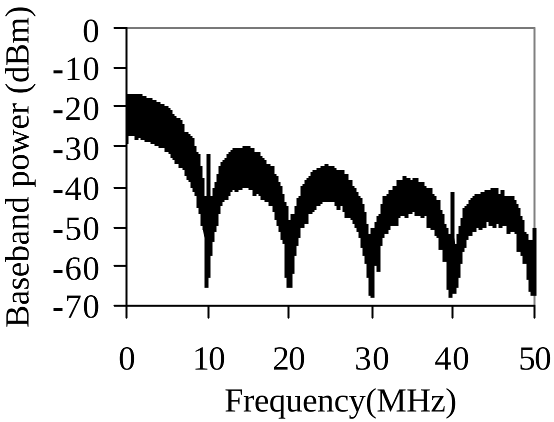



# Measured 10 Mb/s data down-conversion from 14.6 GHz carrier

- **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**

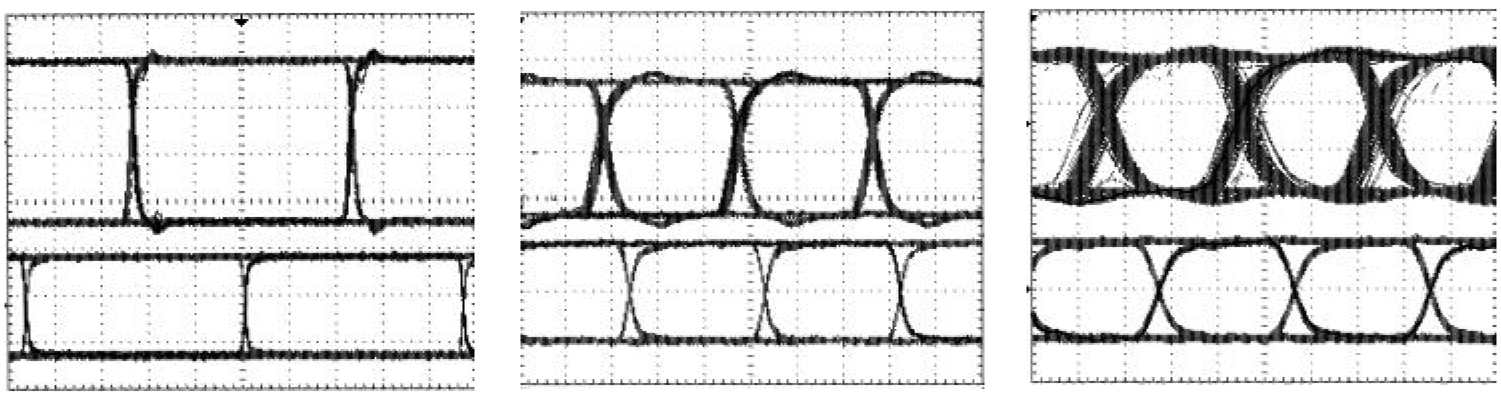


# 10 Mb/s, 50 Mb/s and 100 Mb/s data down-conversion from 14.6 GHz carrier

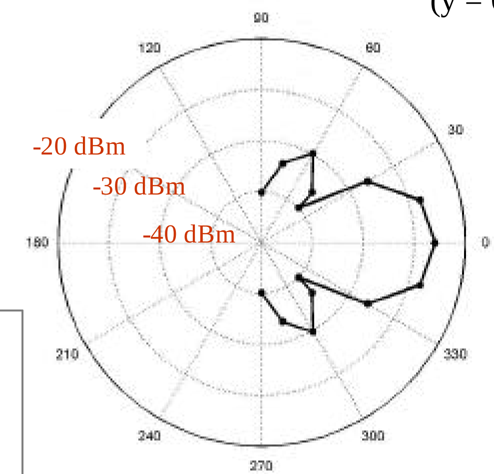
- **Ku-band photonic RF receiver**
  - RF carrier frequency : 14.6 GHz
  - Baseband: 10 Mb/s, 50 Mb/s, 100 Mb/s NRZ PBRS $2^7$-1
  - $m$ = 0.7
  - Received RF power : -15 dBm (integrated power measured within 100 MHz bandwidth centered at 14.6 GHz)

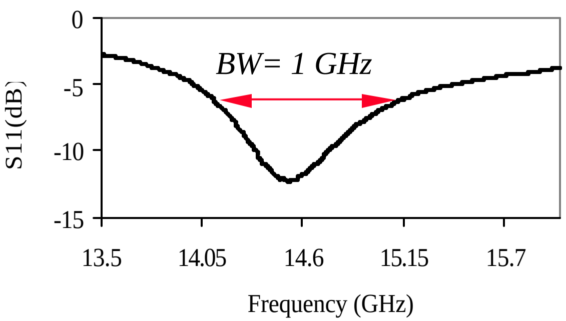


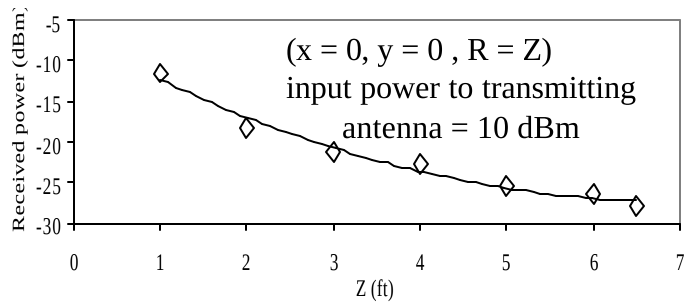
# Measurement of 14.6 GHz patch array performance

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

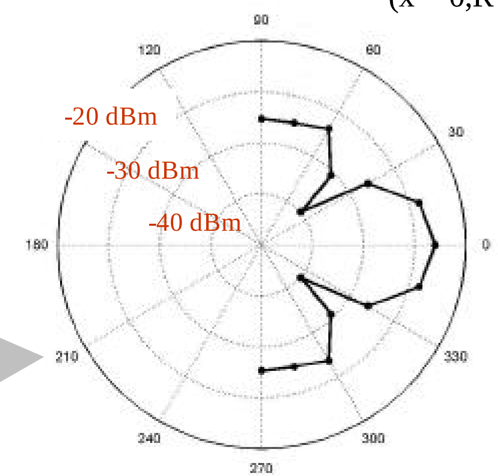
H-plane
(y = 0 ,R = 5.5 ft)

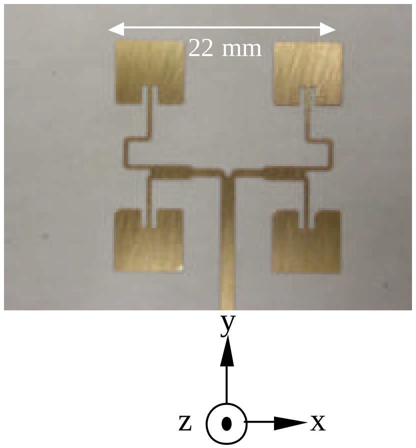


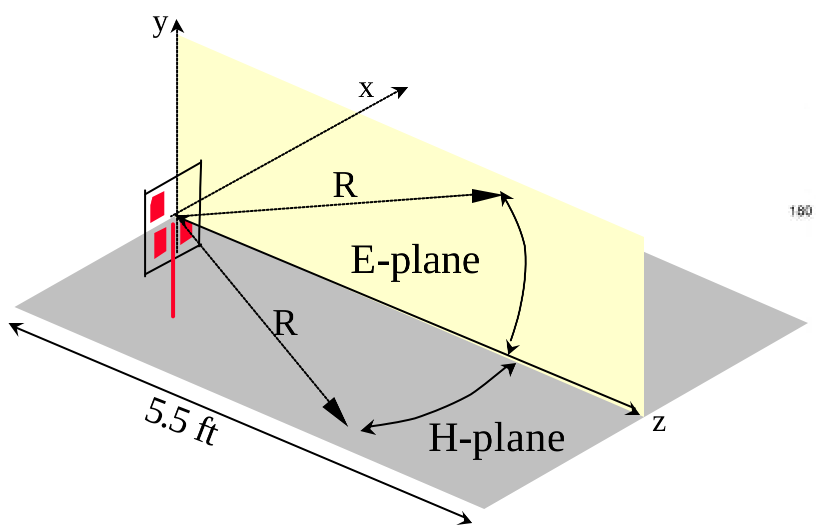



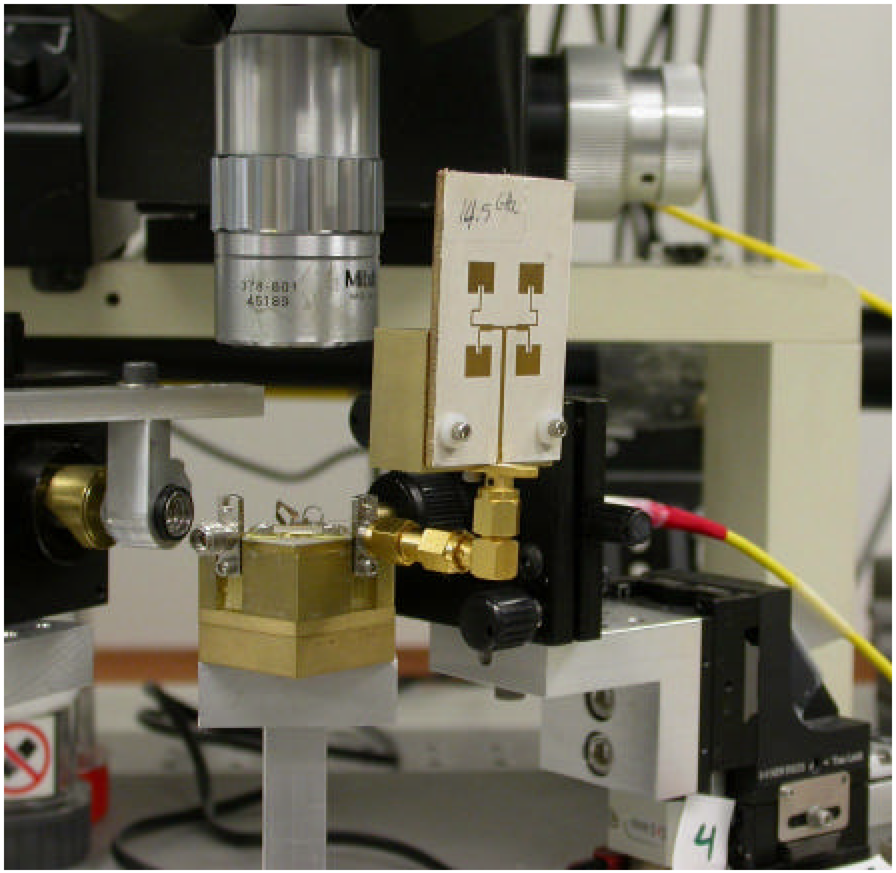

E-plane
(x = 0,R = 5.5 ft)



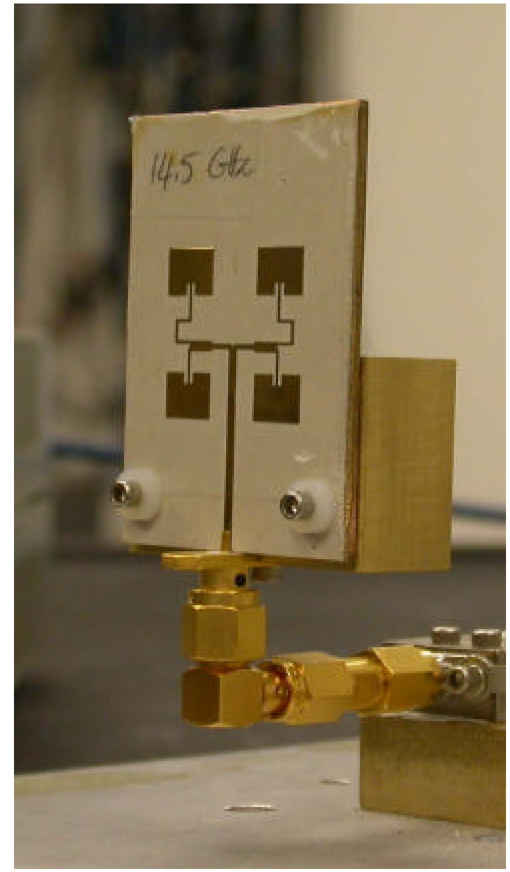



# 14.6 GHz wireless link with microdisk optical receiver



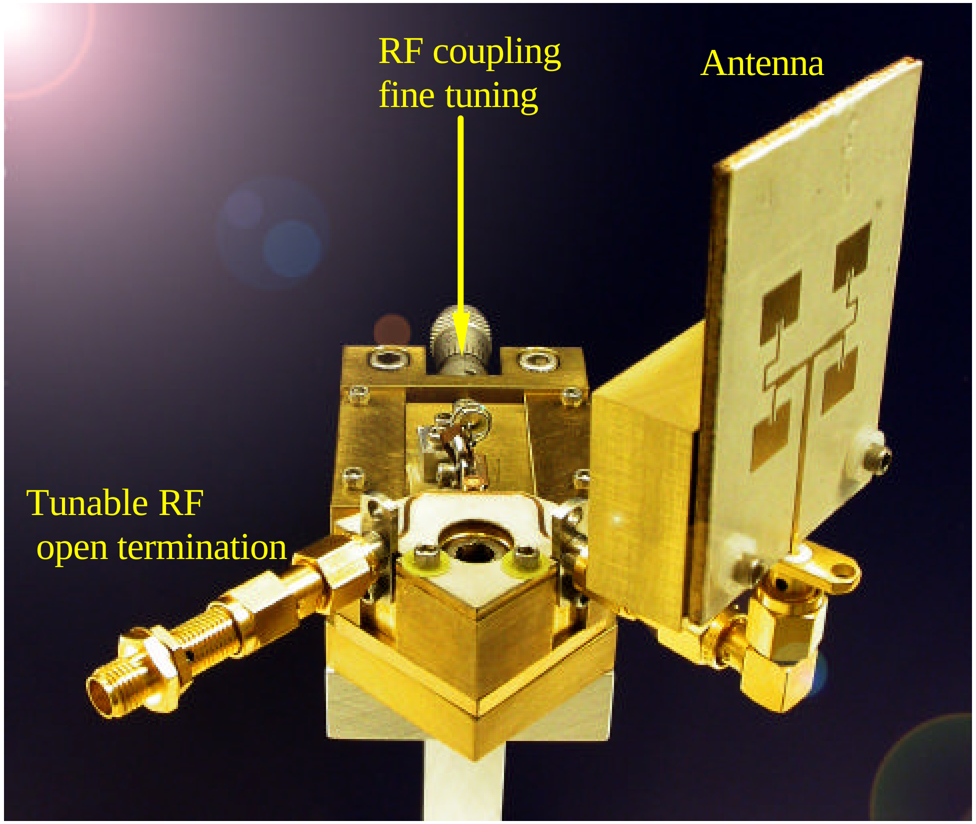
Receiver




Transmitter

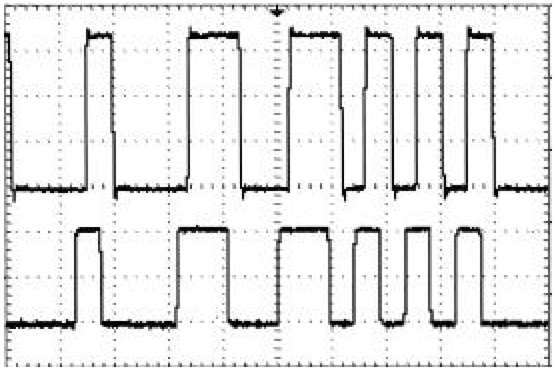
# Wireless data communication with self-homodyne microdisk optical receiver

- **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**



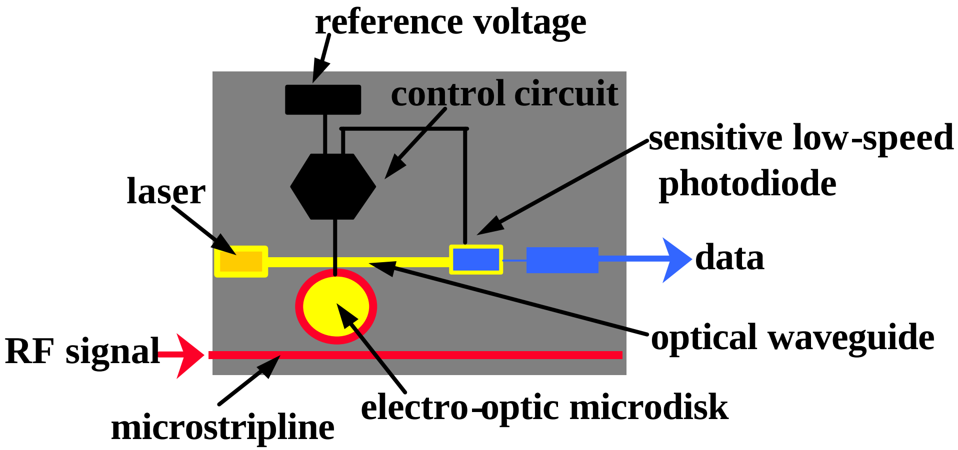

**Down-converted data**

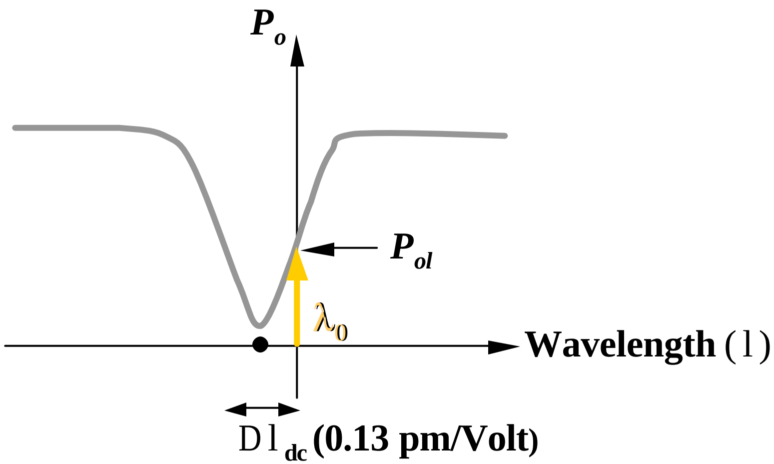
**Original data**



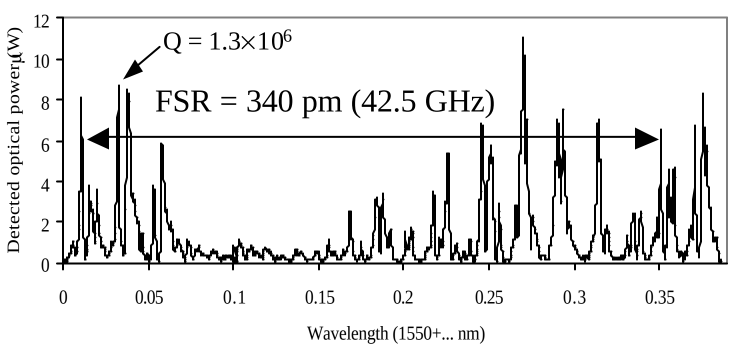
# Future: photonic RF receiver

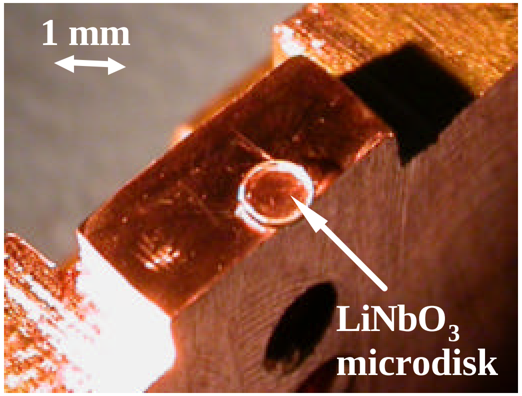
- **Electrical stabilization and wavelength locking (dc bias on electrodes)**
  - **Locking the laser wavelength to a chosen optical transmitted power ($P_{ol}$)**



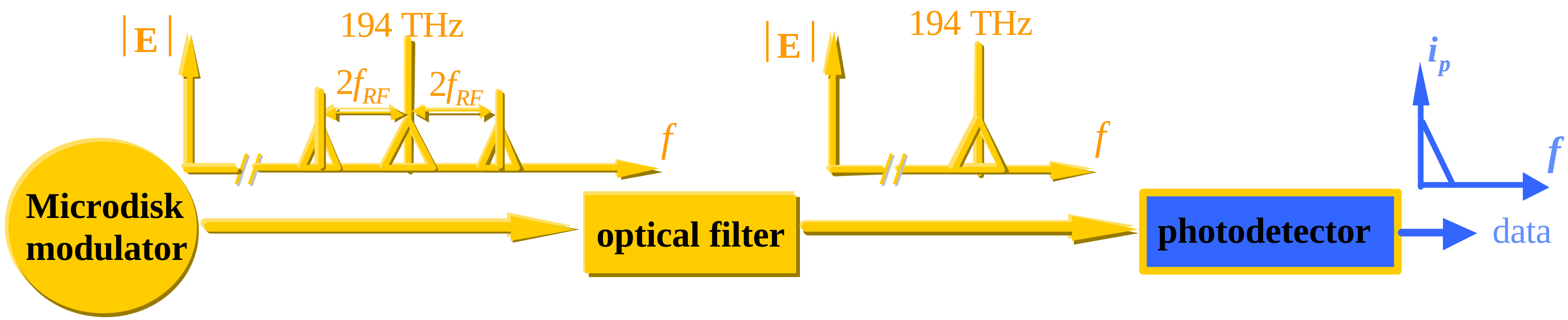

- **Higher carrier frequencies**
  - **Harmonic modulation**
  - **Small disks**



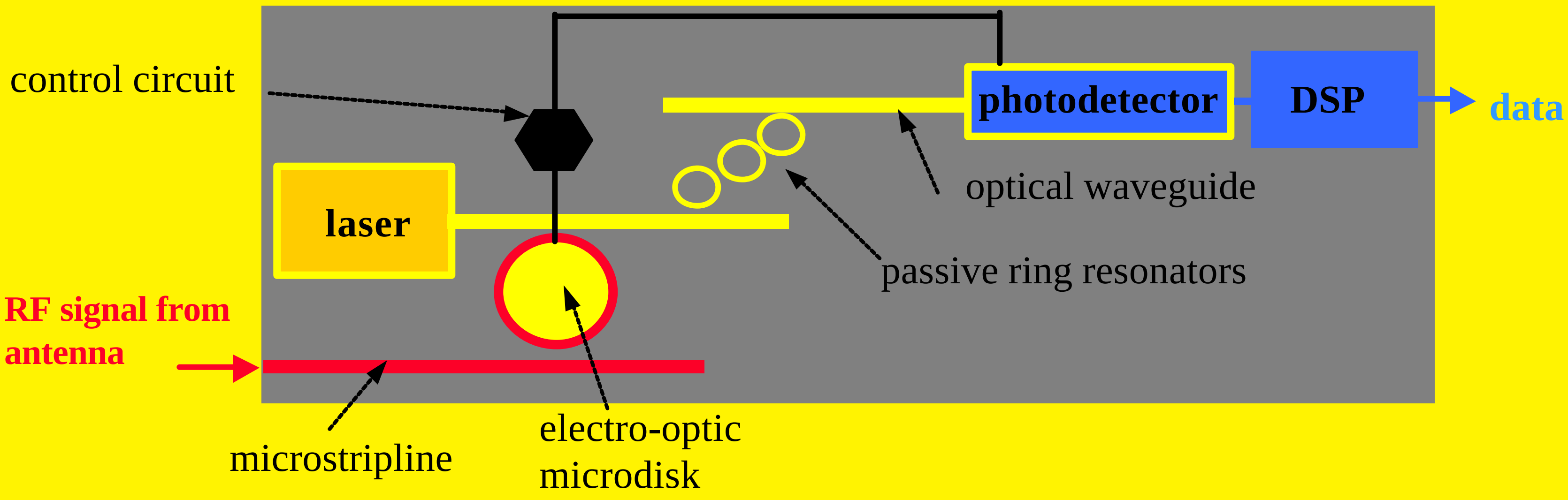



# Future: photonic RF receiver

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

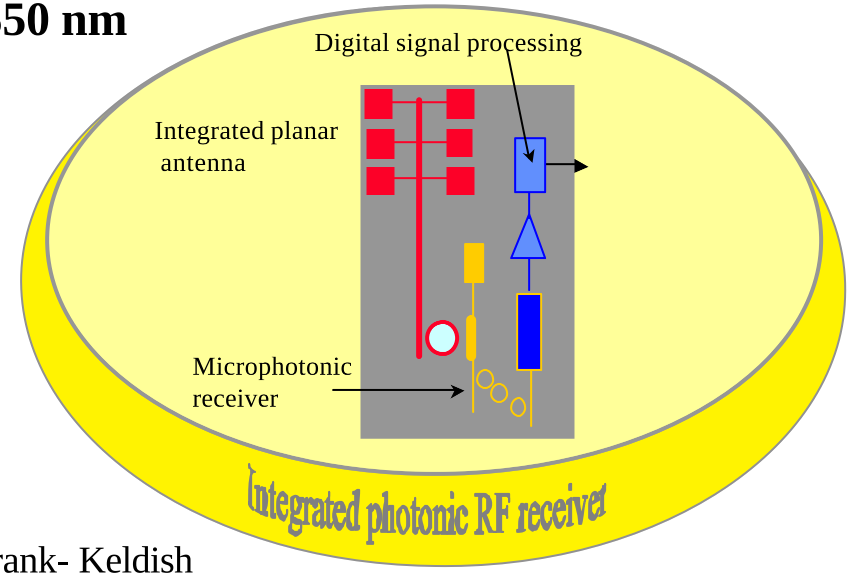



- **Monolithic integration of photonic RF receiver**



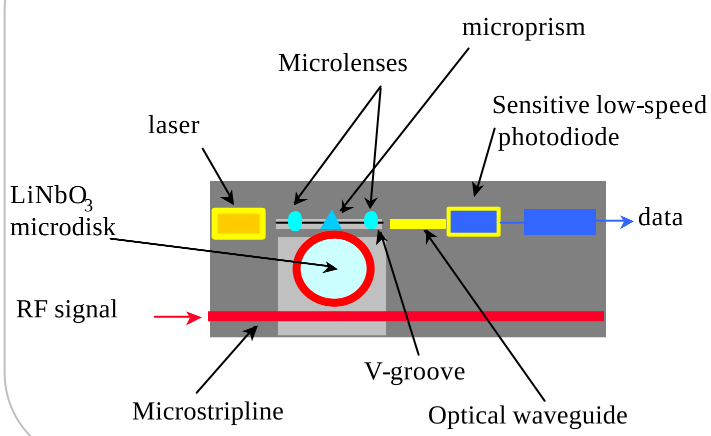
# Future: microdisk photonic RF receiver integration

- **Electro-optic microdisk modulator for l = 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), ……………….



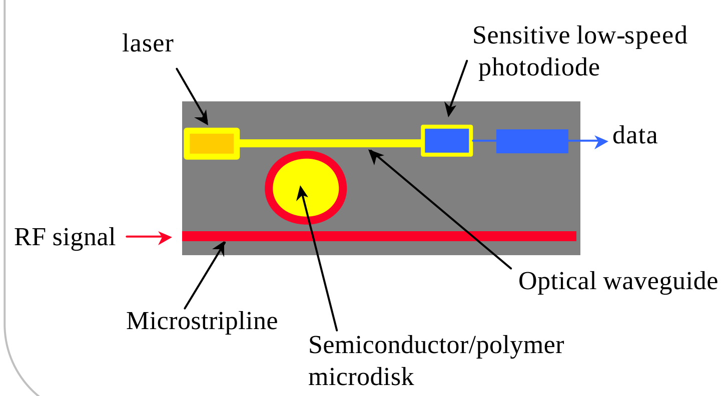

## Hybrid integration (NASA)

**$LiNbO_3$ mounted on Si optical bench**




## Monolithic integration

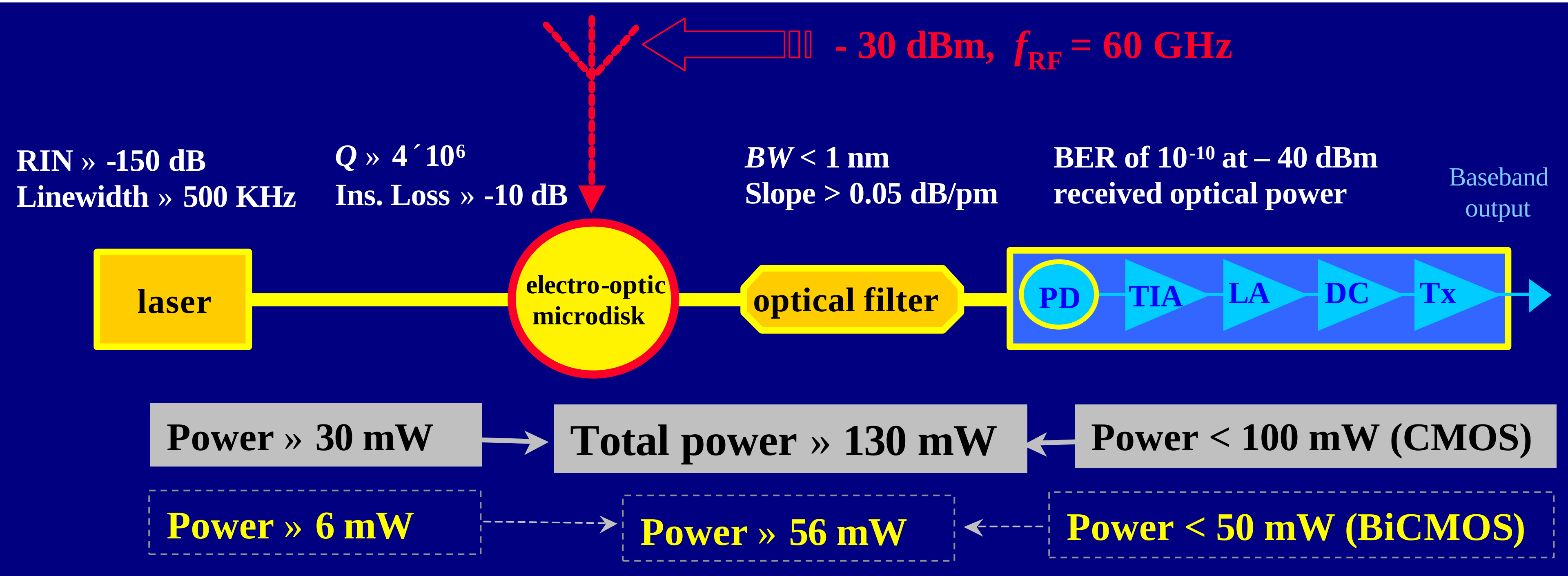
**Semiconductor or polymer (photonic integrated chip)**



# Power efficiency

- **60 GHz monolithic electronic receiver (LNA+LO+MX)**
  (Ref: K. Ohata *et al, IEEE MTT, Vol. 44, Dec 1996* )
  - **0.15 mm N-AlGaAs/InGaAs HJFET MMIC technology**
  - **Power consumption = 400 mW**
  - **Volume: 900 mm$^3$**

- **60 GHz photonic receiver**
  - **No high-speed electronic devices**
  - **Less power consumption (<100 mW)**
  - **Reduced size (< 40 mm$^3$) and complexity**
  - **Reduced cost**

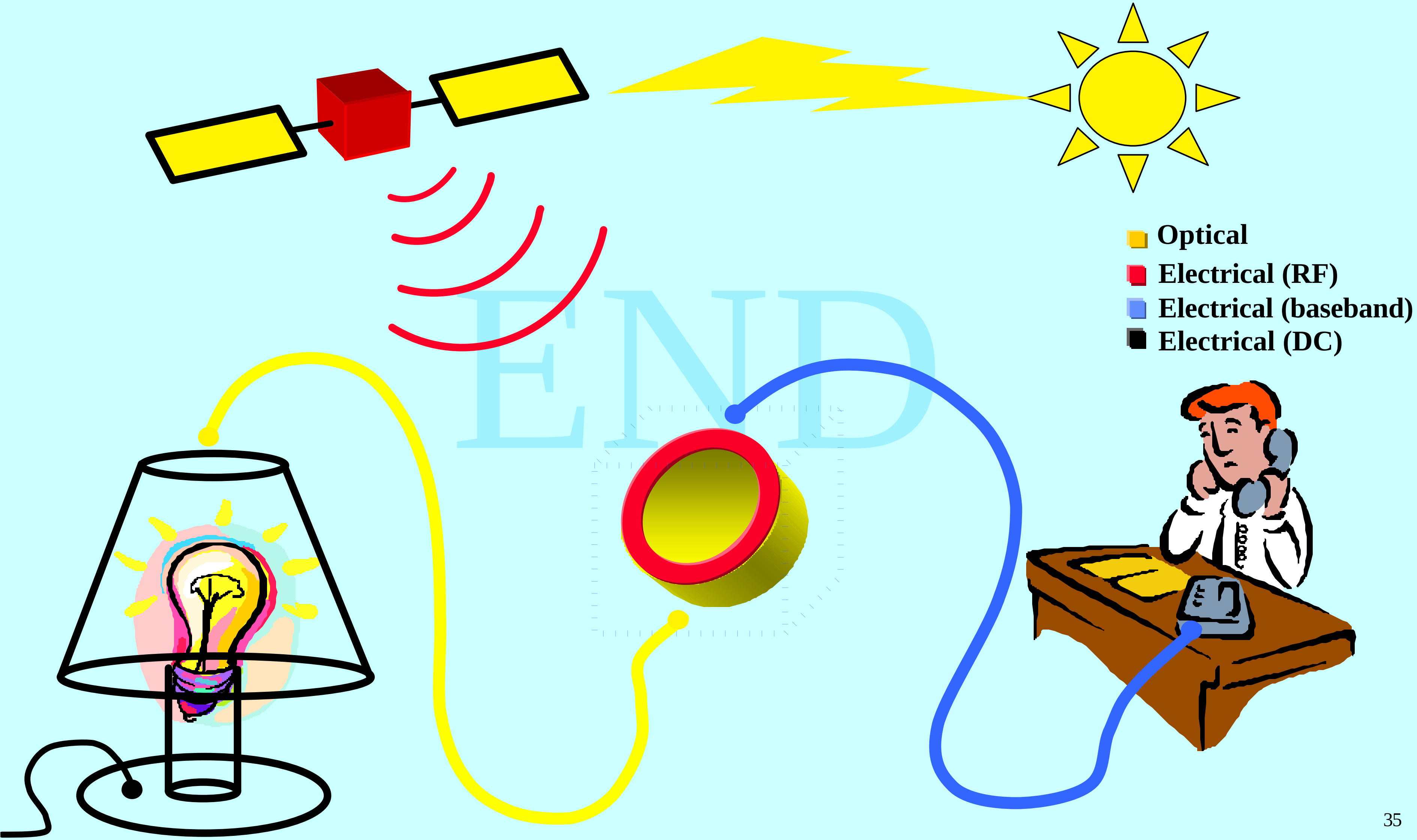


# Conclusion

- 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 $LiNbO_3$ 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.

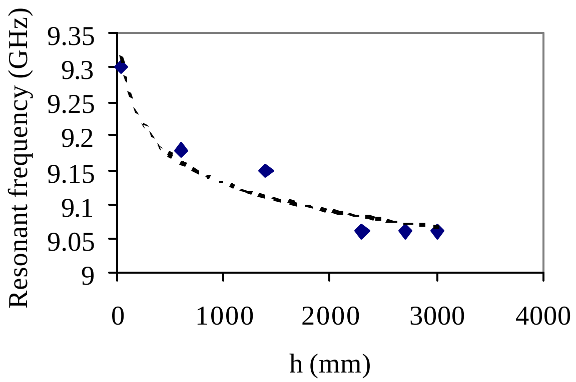
# ELECTROMAGNETIC WORLD!

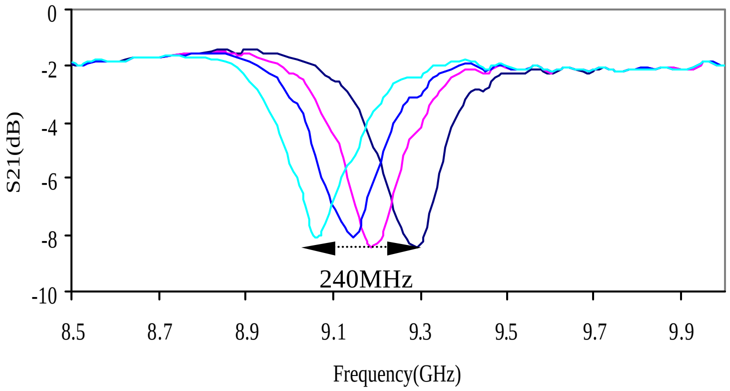
## in which DC-to-light is used for communication

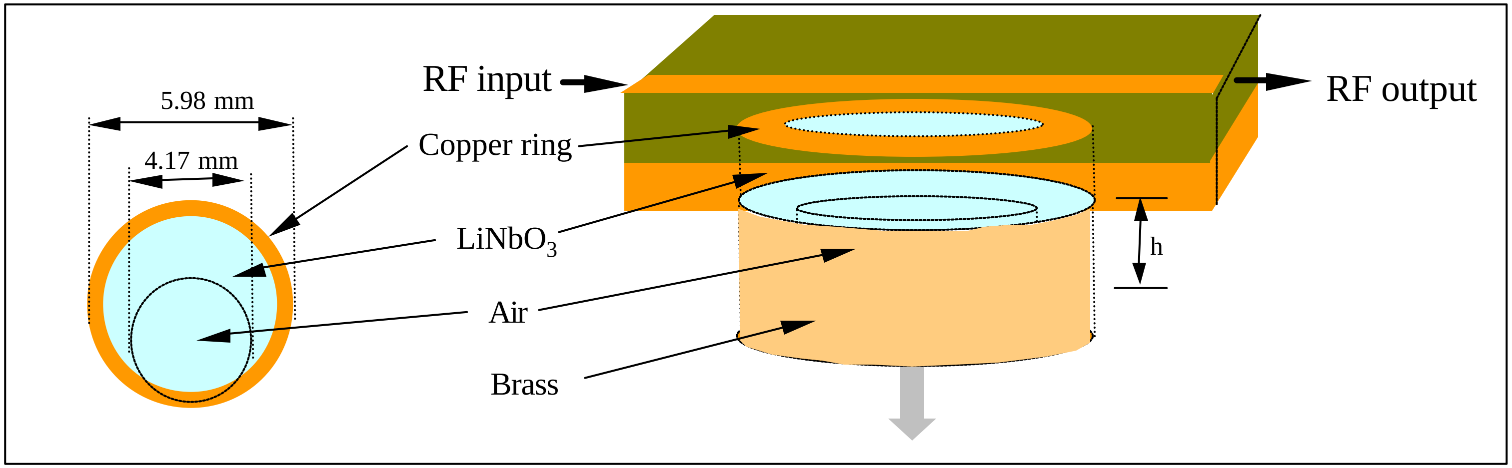


# RF resonant frequency tuning

- **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***

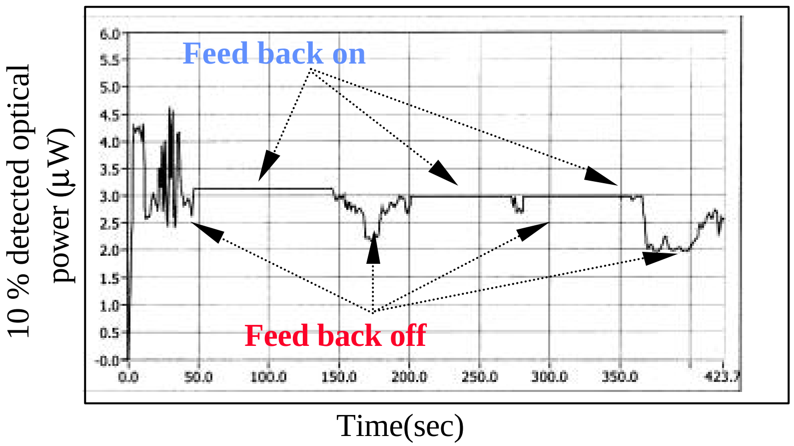


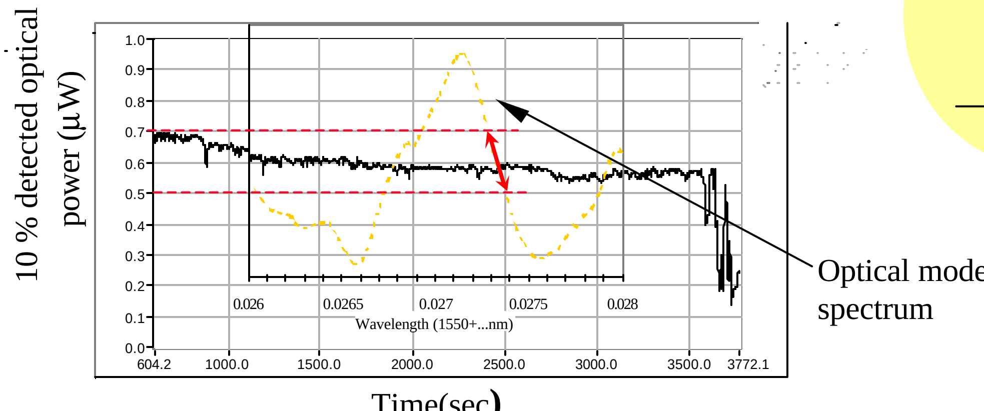



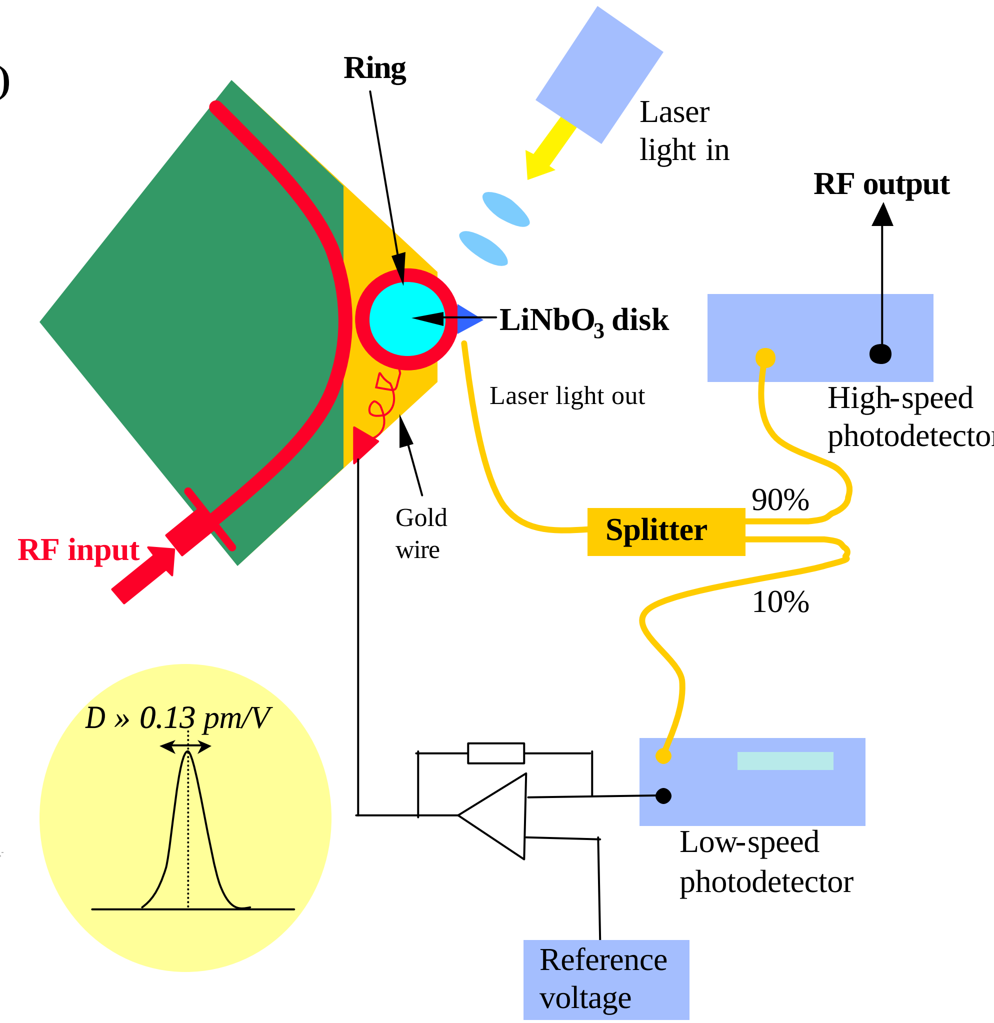



# Feedback loop stabilization

- **Microdisk modulator**
  - **$LiNbO_3$ disk (*D* = 5.13 mm , *h* = 400mm)**
  - **RF ring electrode**
  - **Feedback loop stabilization**
    - **Tuning the resonant wavelengths by DC voltage.**
    - **Locking to maximum slope by feedback loop.**



# Second harmonic modulation

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

**Photons in resonance with even second harmonic mode**