Self-homodyne RF-optical microdisk receiver

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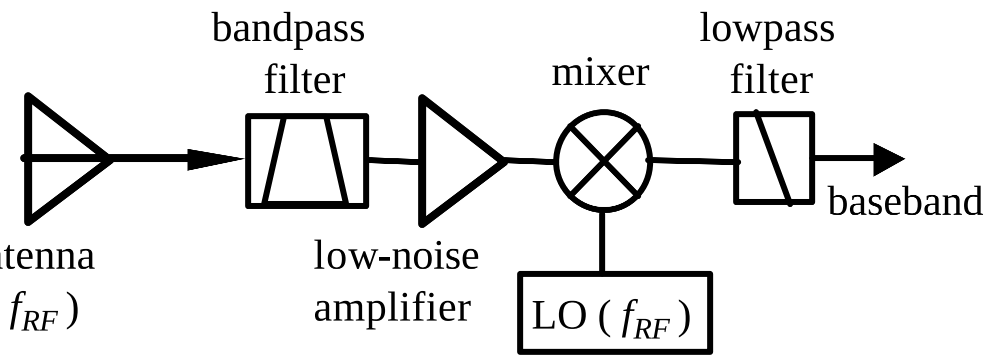
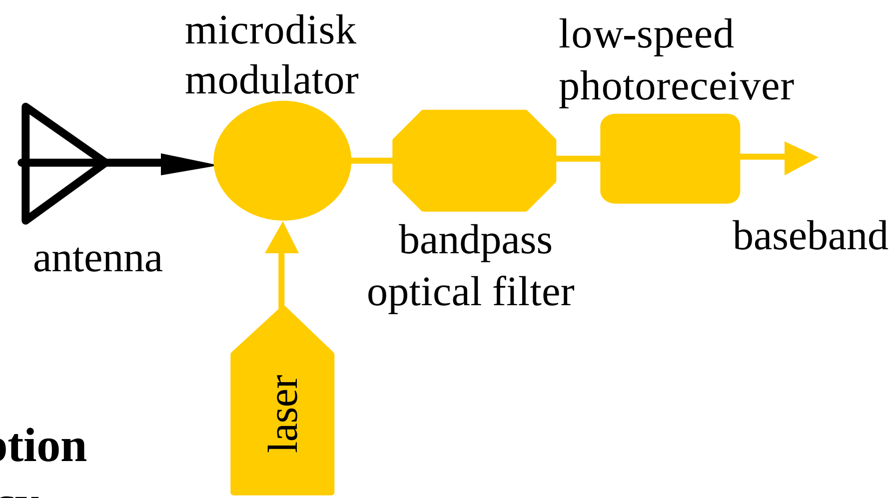
Conventional and microphotonic RF receiver architecture

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

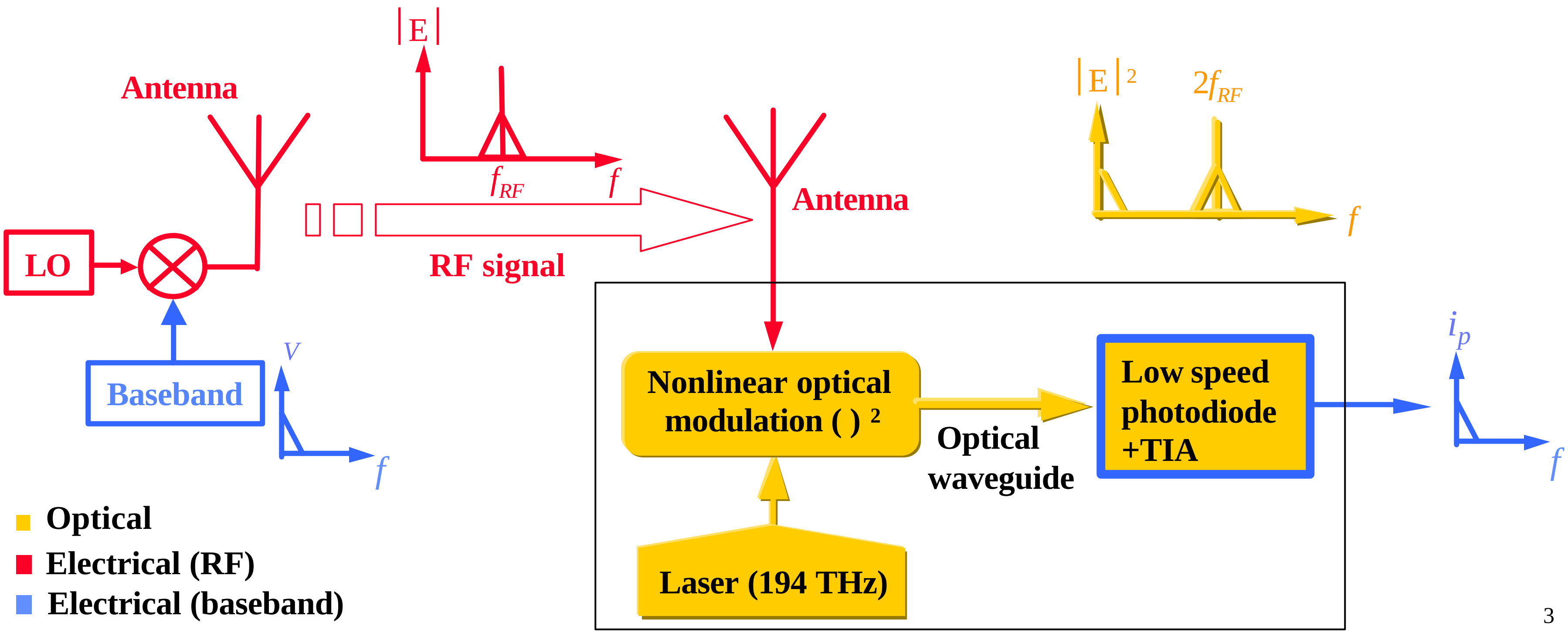


- **Microphotonic RF receiver architecture**
  - **Photonic components**
    - **microdisk optical modulator**
    - **optical filter**
    - **DFB laser**
    - **low-speed photoreceiver**
  - **No high-speed electronics**
  - **No conventional local oscillator**
  - **No RF mixer**
  - **Reduced size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



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 µ V_{RF}^2)**



RF-photonic $LiNbO_3$ microdisk technology

- **$LiNbO_3$ microdisk modulator**
  - **Small volume: 3 mm³ = p×3×0.4 mm³**
  - **large electro-optical coefficient**
    ($r_{33} = 30.8\times10^{-12}$ m/V)
  - **High-*Q* optical whispering-gallery (WG) resonance:**
    2×10^6- 6×10^6 (loaded), 1.2×10^7 (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), $G_v \propto vQ_{RF}$

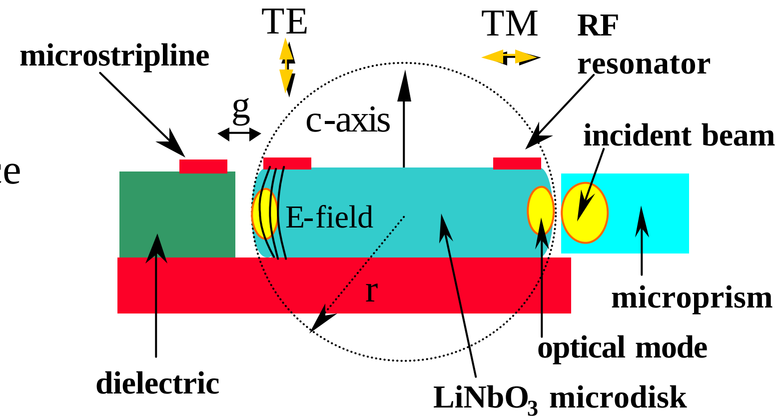
- **RF-photonic application**
  - **Optical modulation**
    - **low power optical amplitude modulation**
  - **RF signal processing in optical domain**
    - **high-frequency operation**
      - low loss in optical domain
    - **reduced power consumption**
      - laser diode local oscillator
    - **optical isolation**

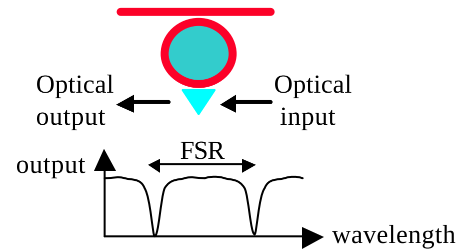
Combination of *microdisk* and *RF-photonic* technology demonstrated in RF-photonic $LiNbO_3$ microdisk receiver

$LiNbO_3$ microdisk modulator

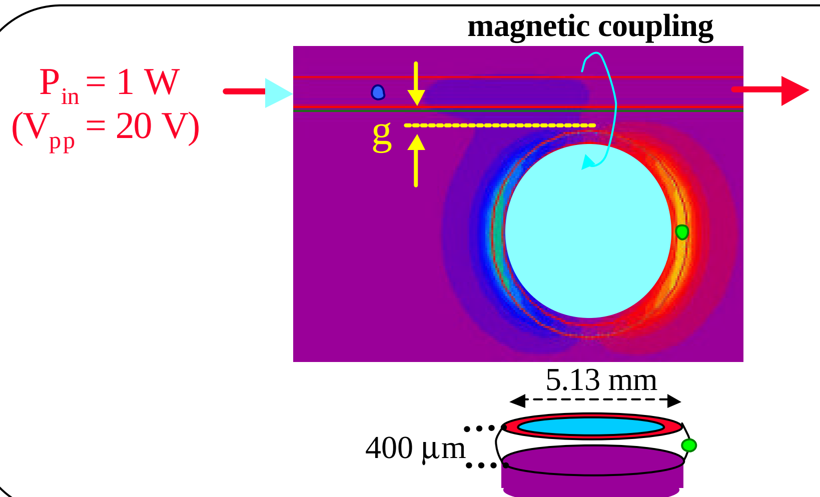
- **$LiNbO_3$ microdisk modulator**
  - **Increased RF sensitivity and low power**
    - RF and optical signal in *simultaneous* resonance
    - RF resonance provides voltage gain
    - high-*Q* (> 10^6) whispering gallery(WG) mode provide long RF-photon interaction time
    - photons highly confined at edge allowing high RF-photon spatial overlap
  - **Modulation only occurs at f_{RF} = *m* ´ n_{FSR} with a bandwidth of Dn = n_0/*Q***

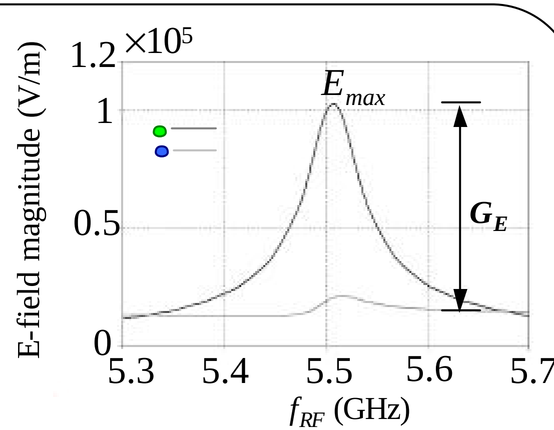
    (n_{FSR}= optical free spectral range, *m* : integer)





Simulated RF resonance





Linear and nonlinear modulation

Received signal

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

Microdisk optical mixer ($l_{laser} = l_{res}$)

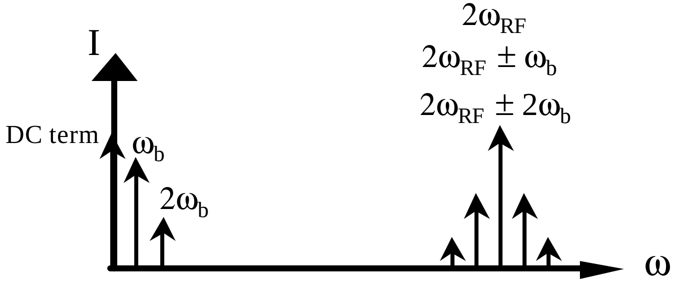
$$P_o(V_{RF}) = N_0 + \frac{1}{2}N_2V_{RF}^2 + \ldots$$

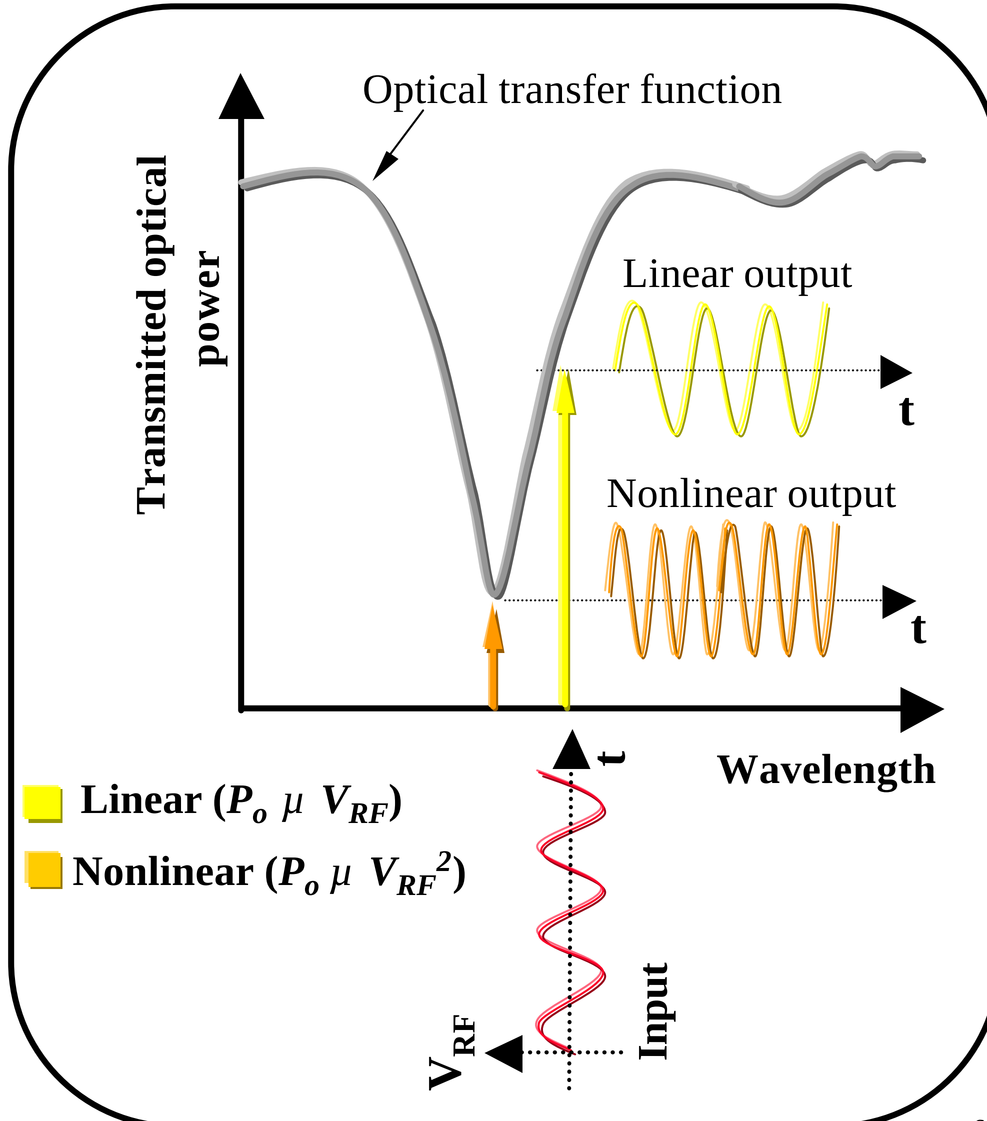
$$N_2 = \left.\frac{d^2P_0}{dV_{RF}^2}\right|_{V_{RF}=0} = f(G_V, Q, P_{o,in}, k, b_E, t)$$

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

$$I(V_{RF}) = RP_o(V_{RF}) = R(N_0 + \frac{1}{2}N_2V_{RF}^2 + \ldots)$$

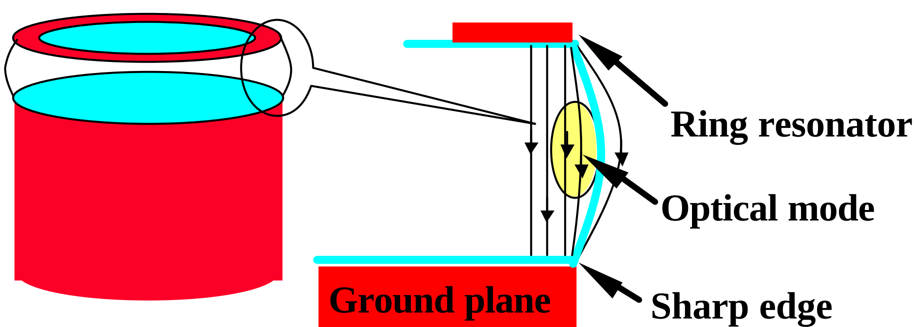
$$I_{w_b} \approx R\frac{m}{2}N_2V_{RF}^2$$

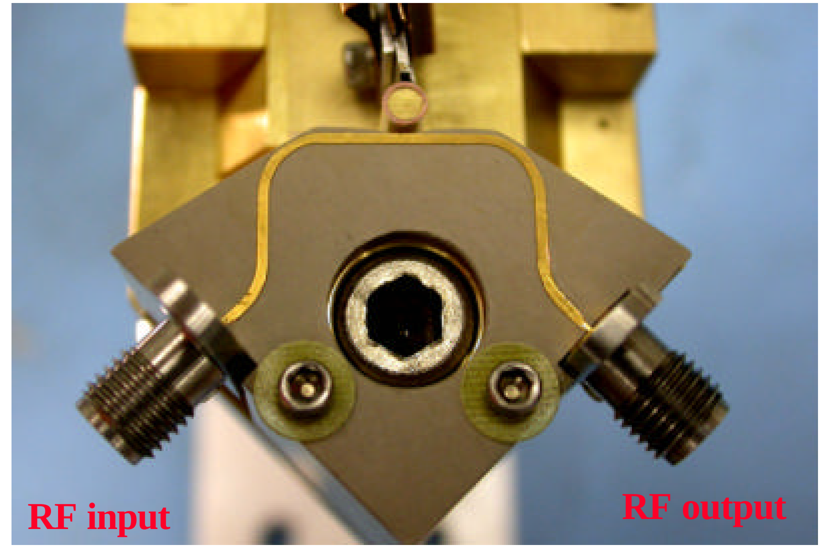


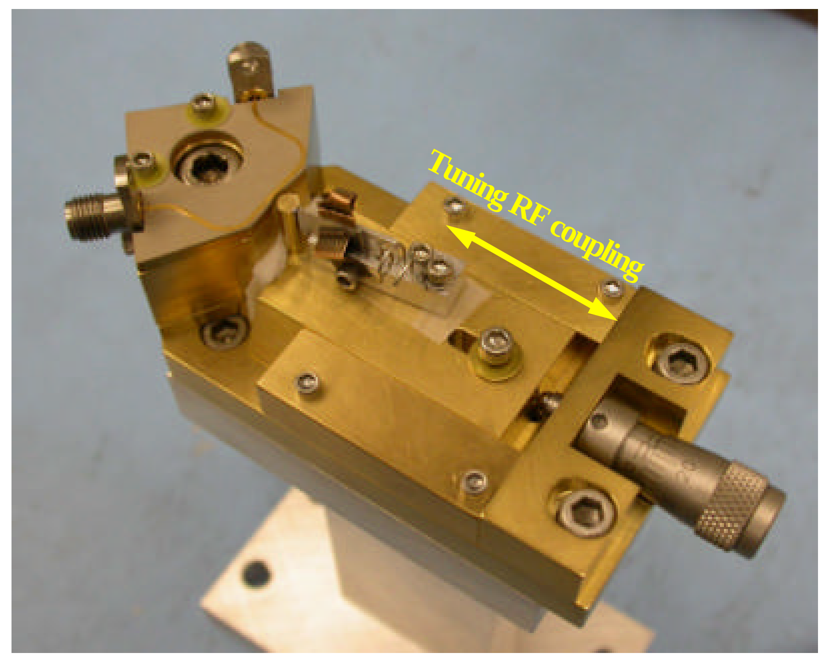


14.6 GHz $LiNbO_3$ microdisk modulator

- **14.6 GHz $LiNbO_3$ microdisk modulator**
  - **3 mm diameter $LiNbO_3$ microdisk**
    - $D = 3$ mm, $t = 400$ 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 300 μm gap.
  - **Modified E-field distribution**
    - cylindrical symmetric E-field distribution
    - enhanced E-field intensity

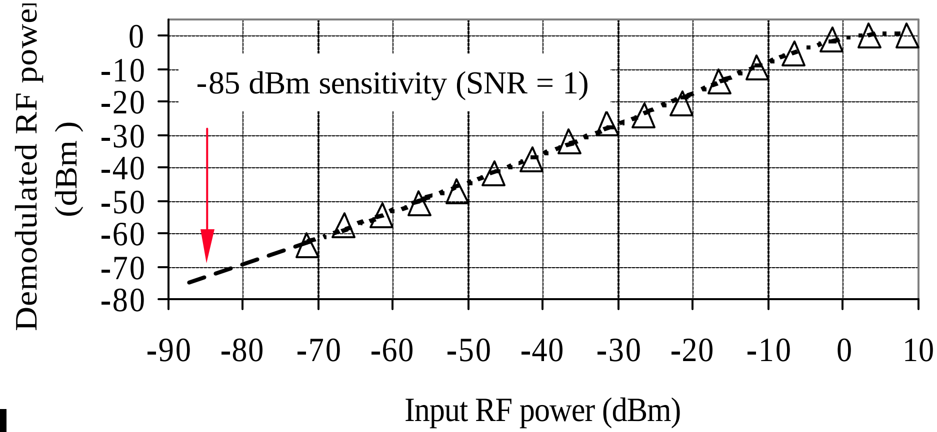


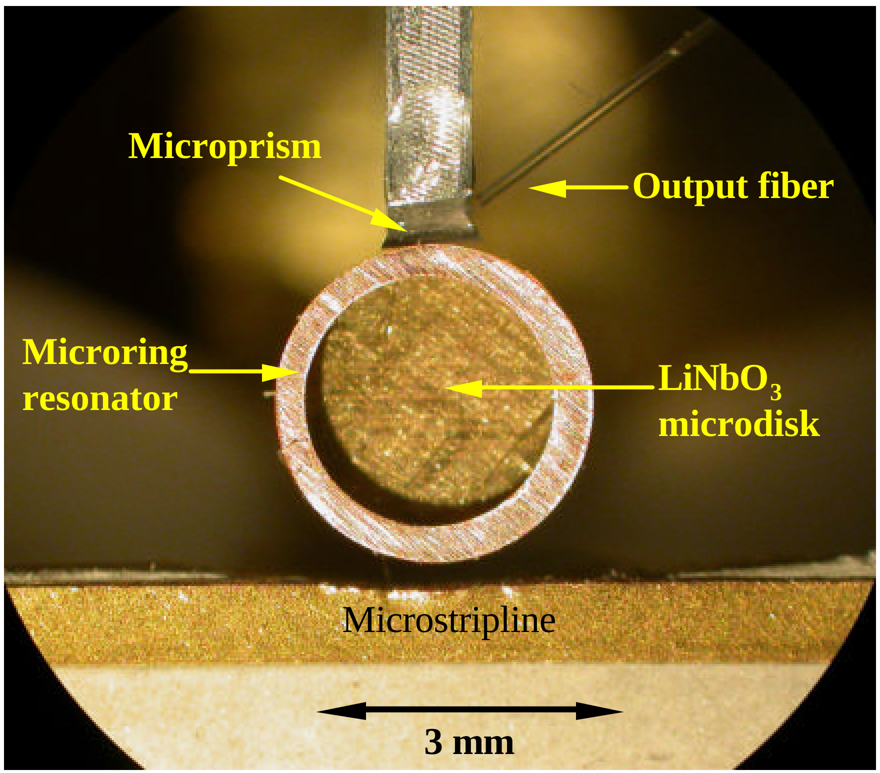


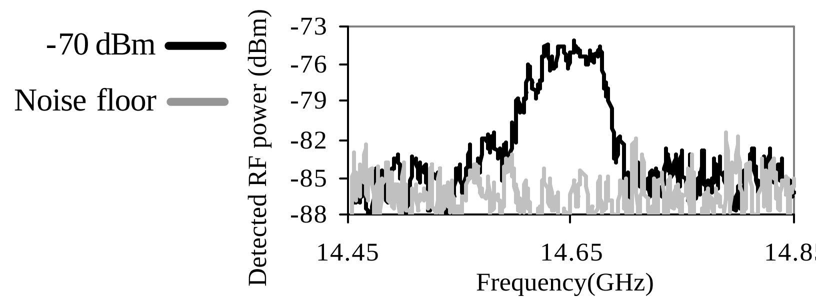


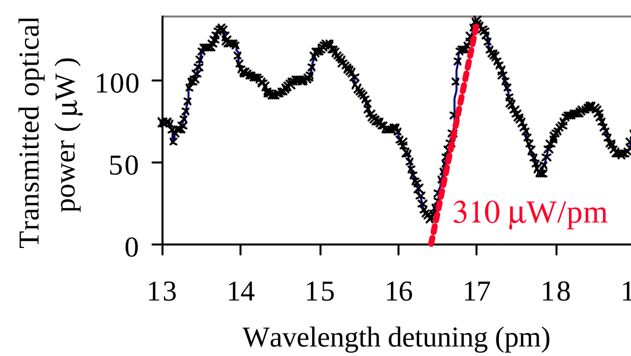
Power sensitivity of single-frequency linear modulation at 14.6 GHz

- **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**





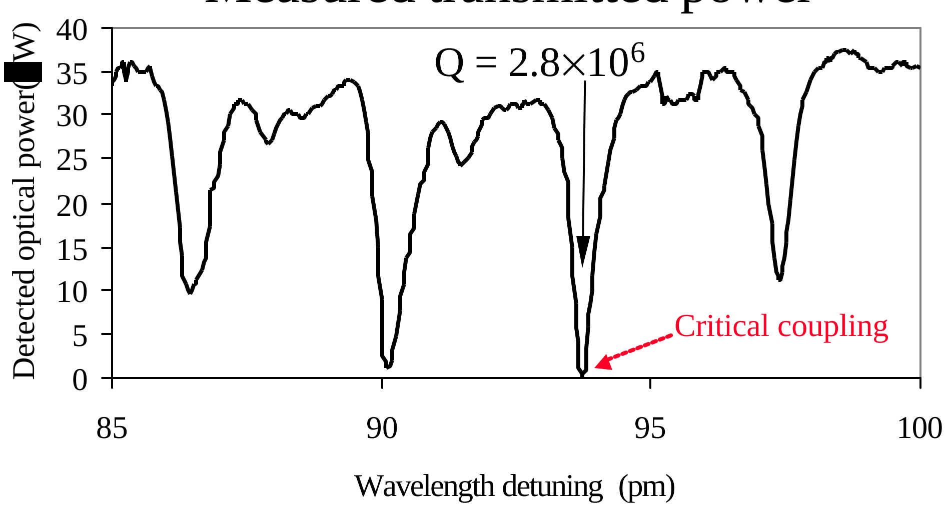




Critical optical coupling and second-order nonlinear modulation with microdisk modulator

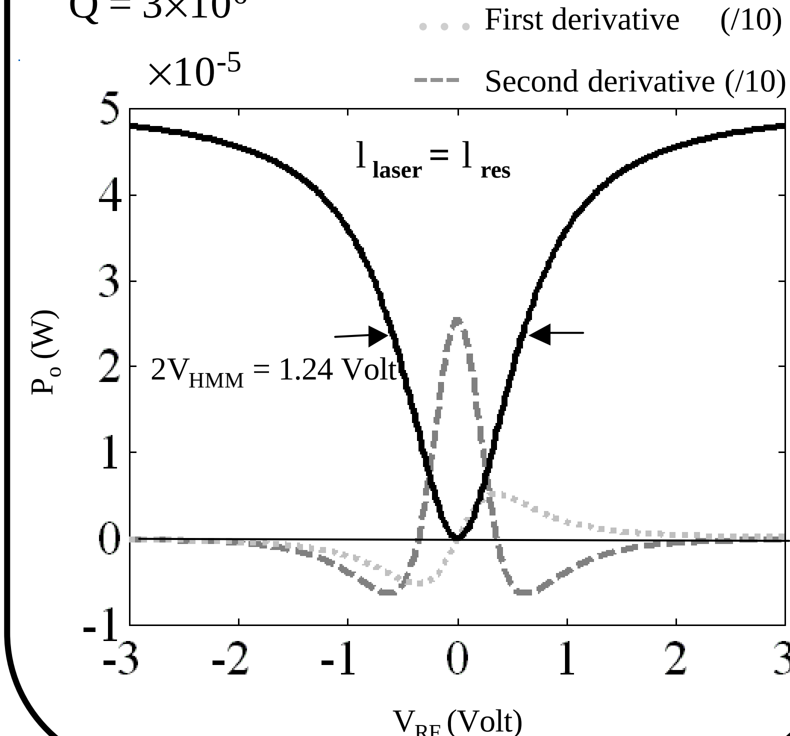
- **Transmission dips**
  - **Zero DC optical power (at $l_{laser} = l_{res}$) with critical coupling**
    - **reduction of optical noise generated by DC optical power**
  - **Large second-order nonlinearity**

Measured transmitted power



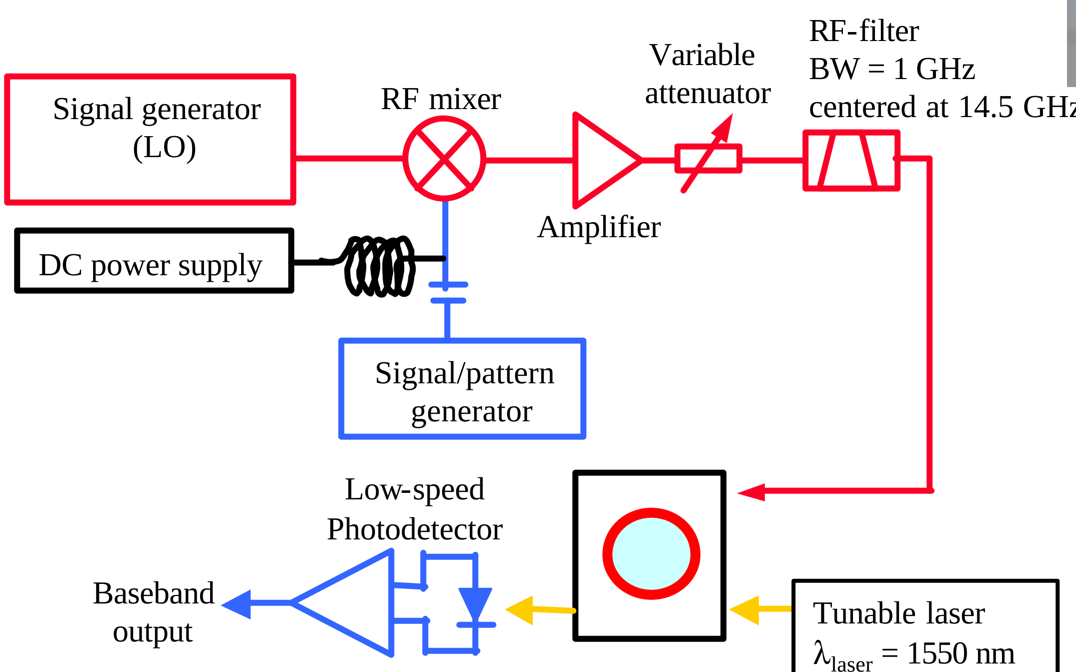
Simulation

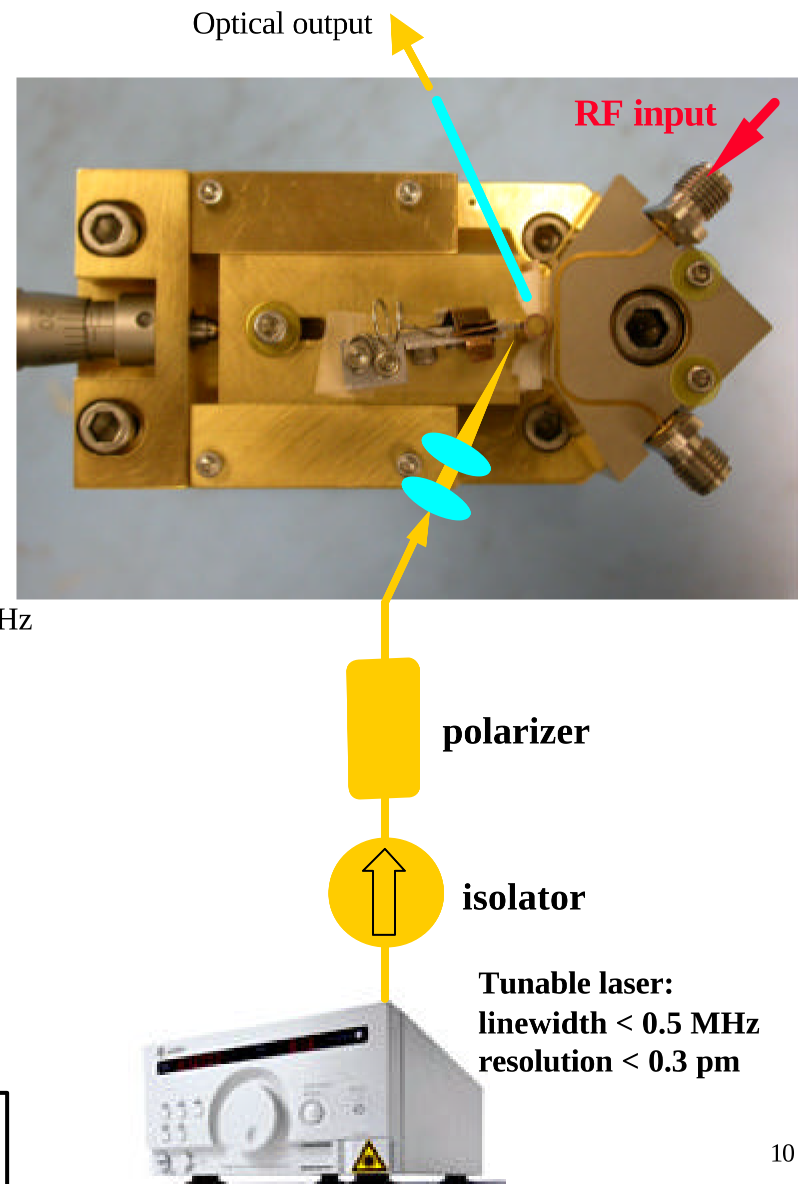
Optical input power = 50 µW
Optical coupling factor (κ)= 0.114
Distributed loss (/cm) = 0.0075 (Q = 1.2×10^7)
DC shift = 0.135 pm/V
Voltage gain factor (Volt) = 6
Q = 3×10^6



Experimental arrangement

- **Direct down-conversion RF-photonic link**
  - **Transmitted carrier RF format**
    - **DC biased mixer (IF port) to control modulation index (*m*)**

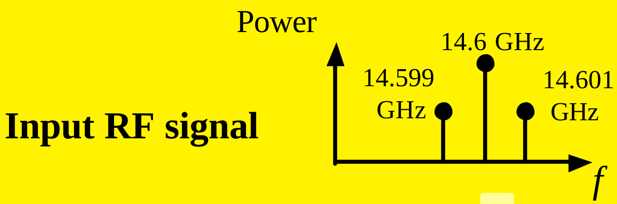


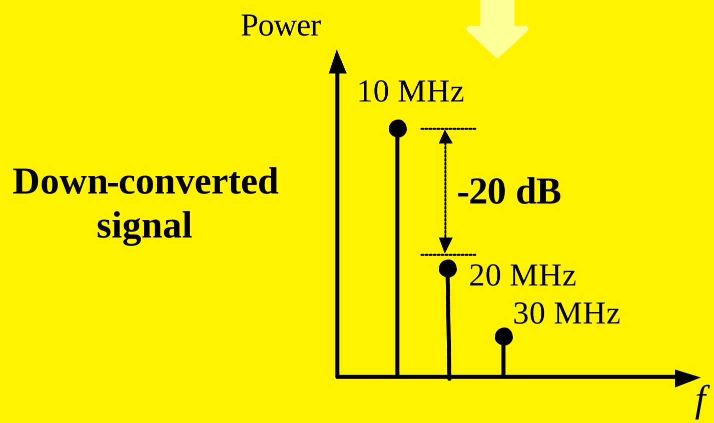


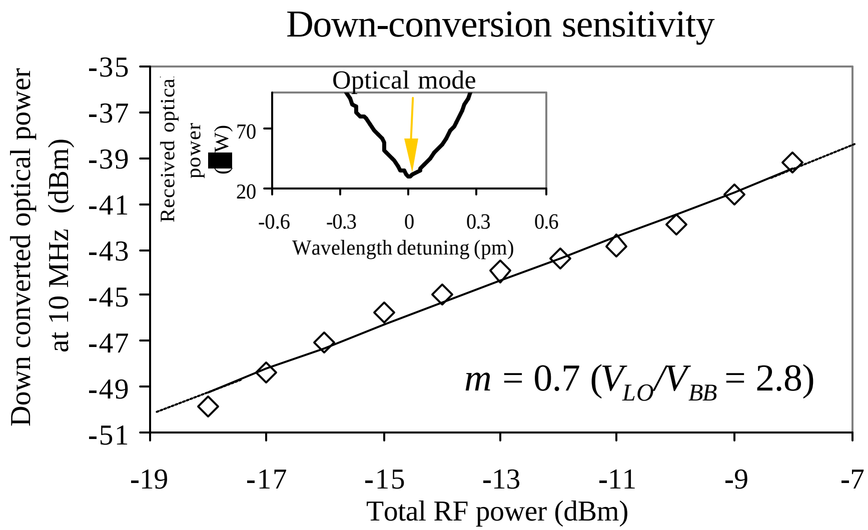
Single tone down-conversion

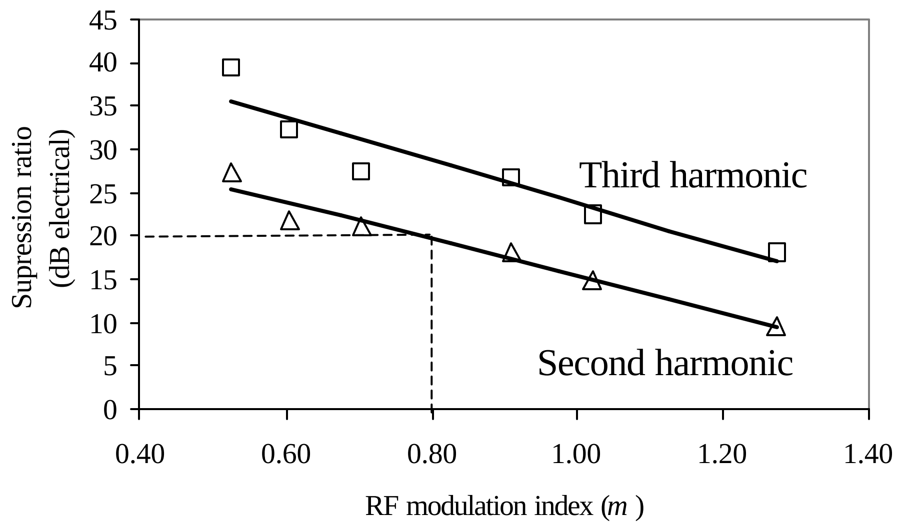
- **RF input signal**
  - **Carrier frequency = 14.6 GHz**
  - **Baseband frequency = 10 MHz**
  - **Transmitted carrier format**
- **Photodetector**
  - **Responsivity: 3 mV/mW**
  - **Bandwidth: 100 MHz**

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



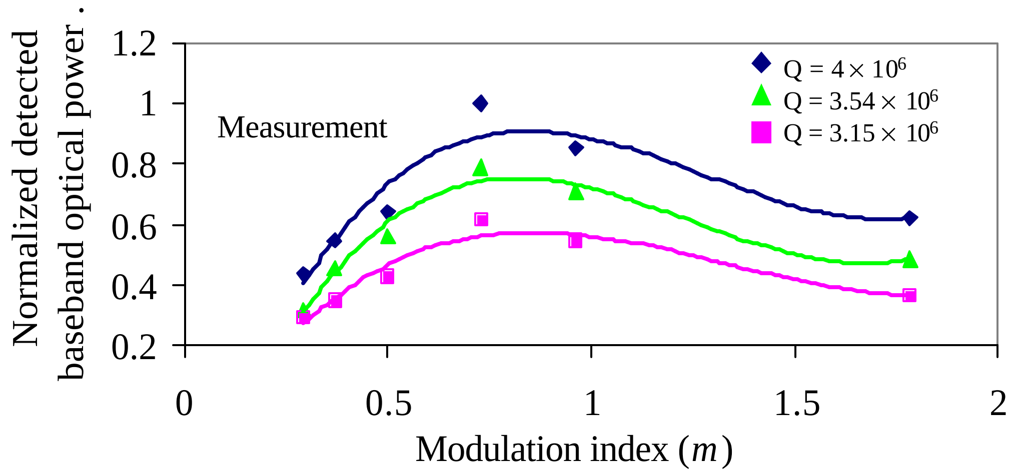






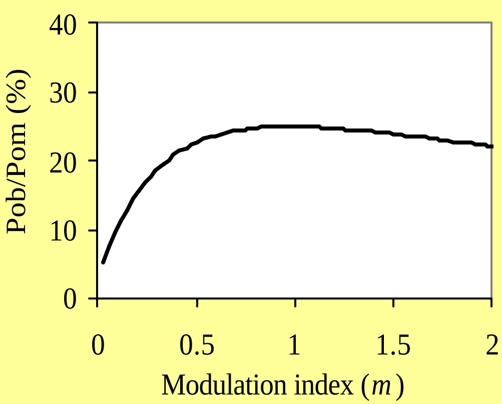
Optimizing modulation index for single frequency down-conversion efficiency

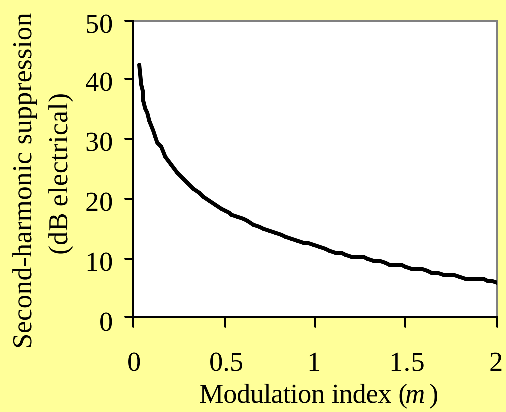
- **RF modulation format effect**
  - **Total received RF power » -15 dB**
  - **Transmitted carrier format**
    - **modulation index *m* < 2**
  - **Optimized modulation index**
    - **measurement *m* » 0.7**
    - **calculation (square law response) *m* » 0.7**



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)





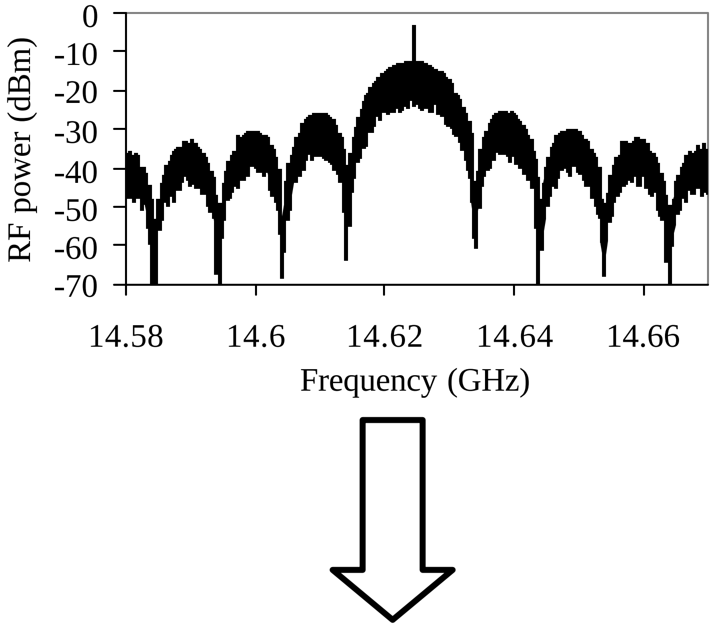
At small signal regime (P_{RF} < -10dBm) a modulation index of *m* = 0.7 results in 25% down-conversion efficiency and about 15 dB second-harmonic suppression ratio.

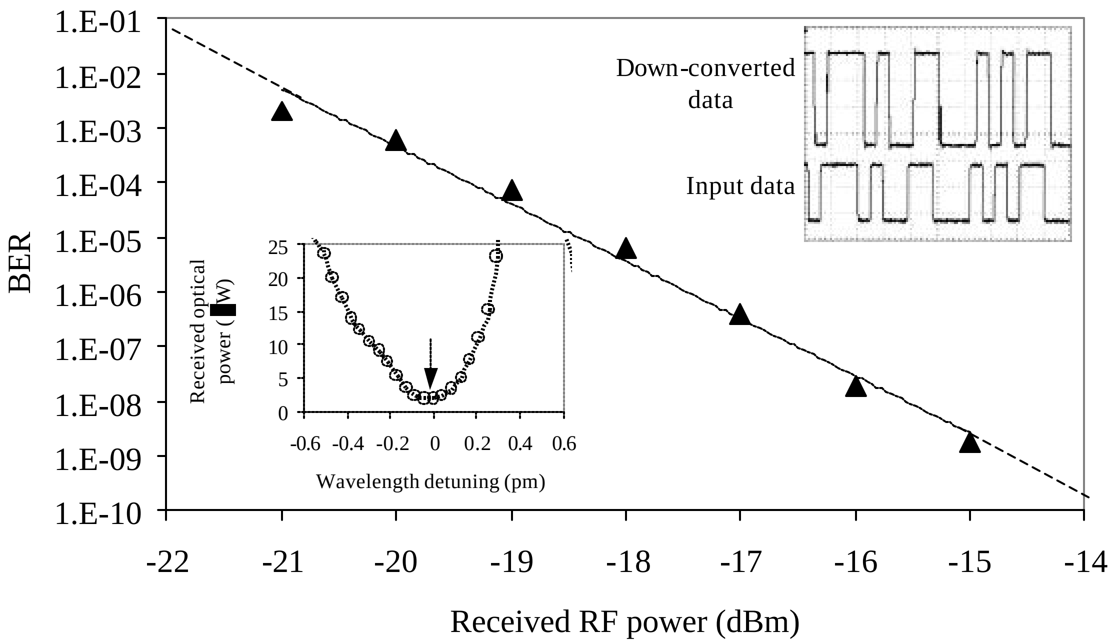
Conclusion

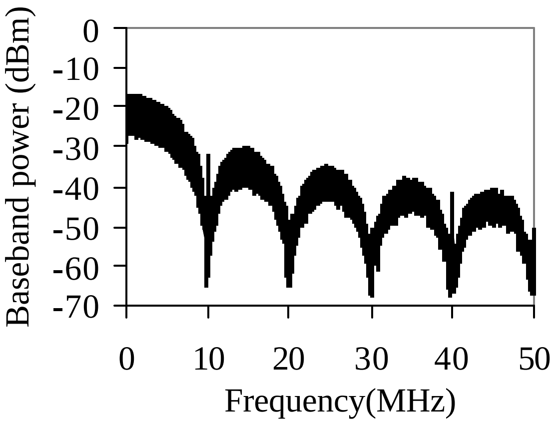
- **0.7< *m* <0.8 simultaneously optimizes linearity and efficiency of the conversion**

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: -34.5 dBm**
    - **bandwidth: 100 MHz**

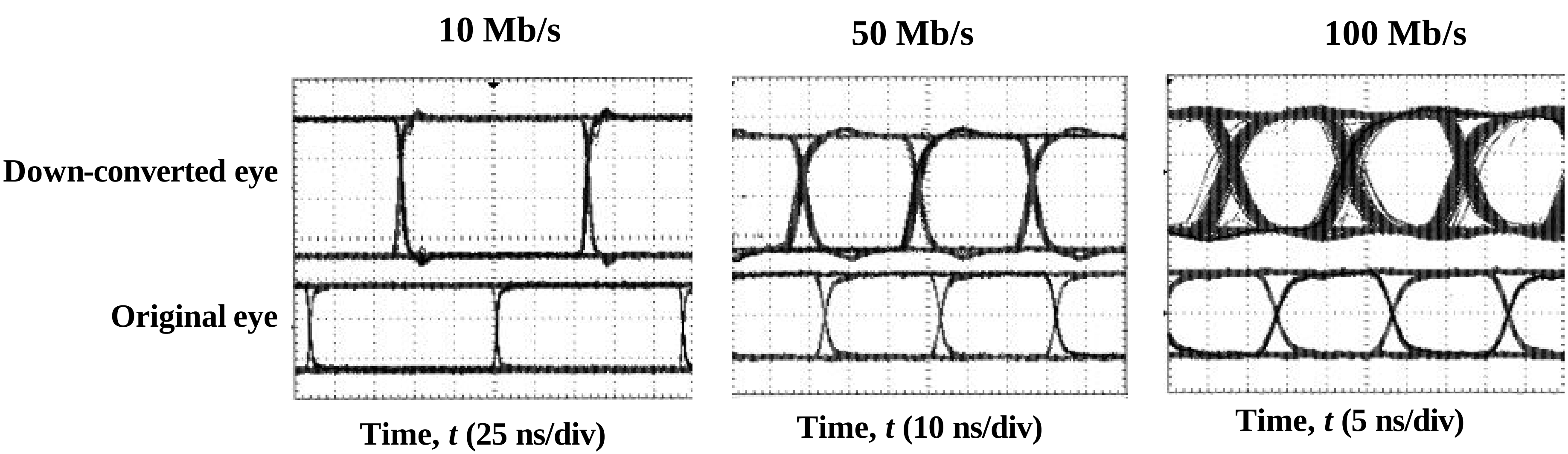






10 Mb/s, 50 Mb/s and 100 Mb/s data down-conversion from 14.6 GHz carrier

- **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)**

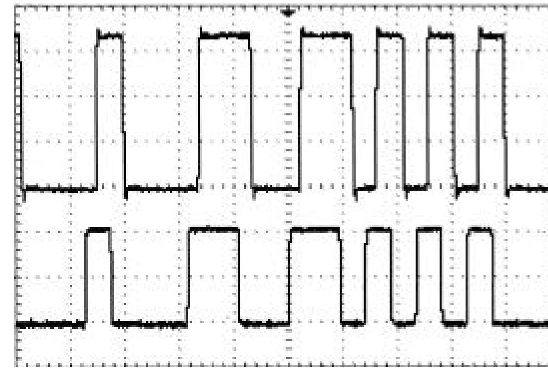


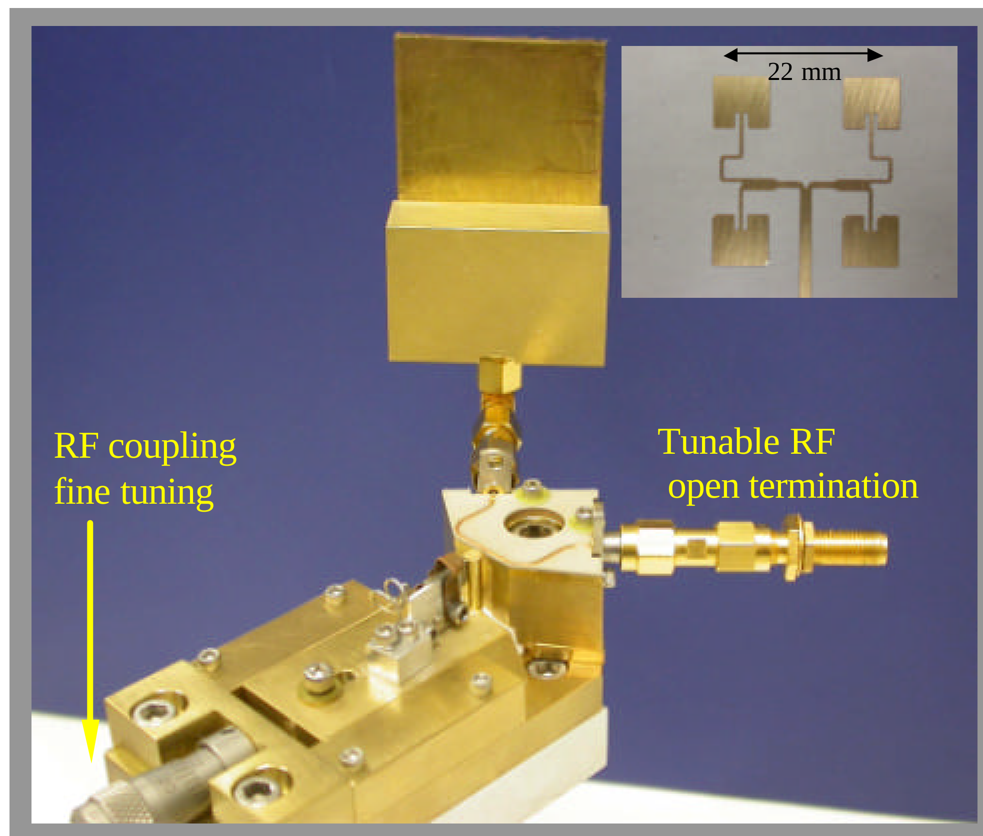
Wireless data communication with self-homodyne microdisk optical receiver

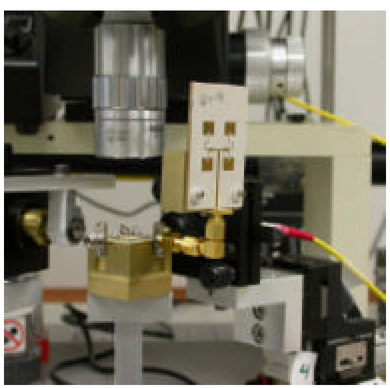
- **Wireless self-homodyne microdisk RF-photonic receiver**
  - **14.6 GHz 4-patch antenna array**
  - **High sensitivity microdisk optical modulator**
  - **RF-photonic nonlinear modulation**
  - **Carrier frequency : 14.6 GHz**
  - **Modulation index: *m* = 0.8**
  - **Baseband: 10 Mb/s NRZ PBRS 2^7-1**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

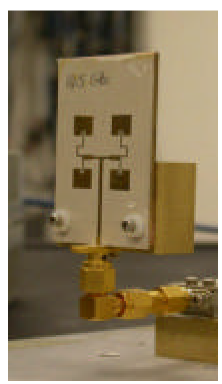
Down-converted data

Original data



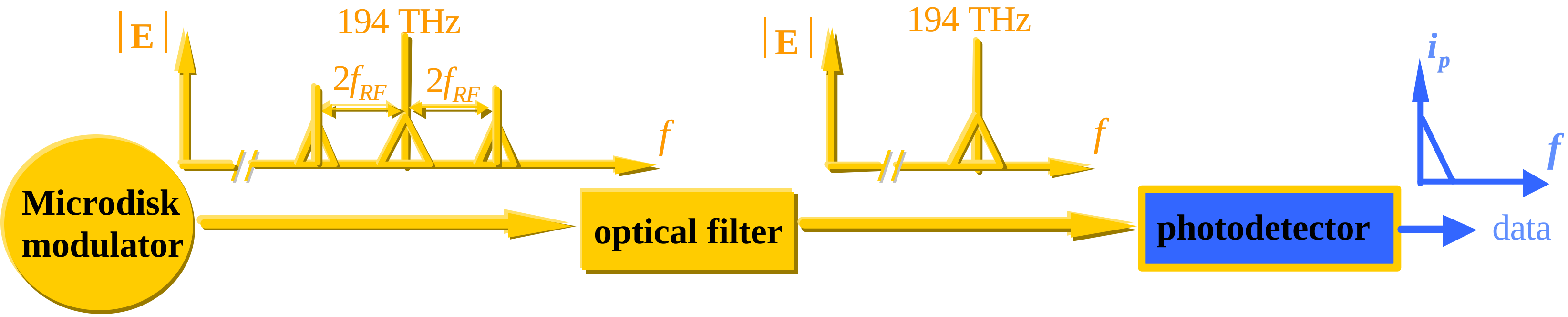




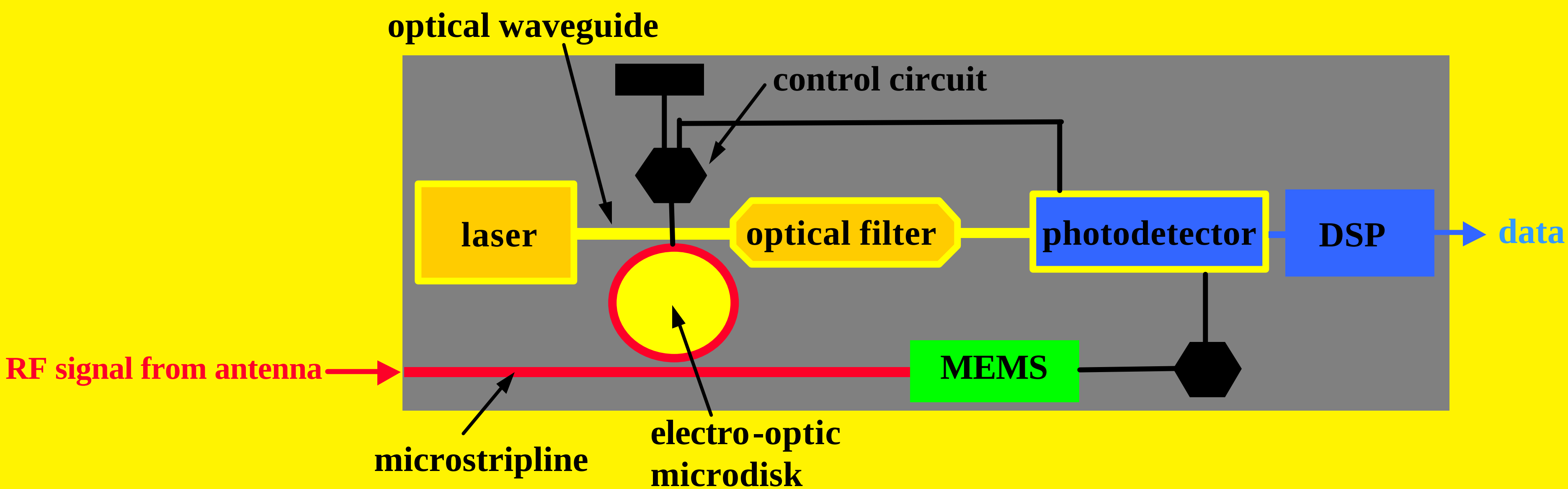


Future: Photonic RF receiver

- **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**



ELECTROMAGNETIC WORLD!

in which DC-to-light is used for communication