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PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

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DEμS

Very High Data Rate Optical Wireless Communication with Micro Organic LED

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Li-Fi Conference

27 June 2023
High Tech Campus Eindhoven /
Online (Hybrid)
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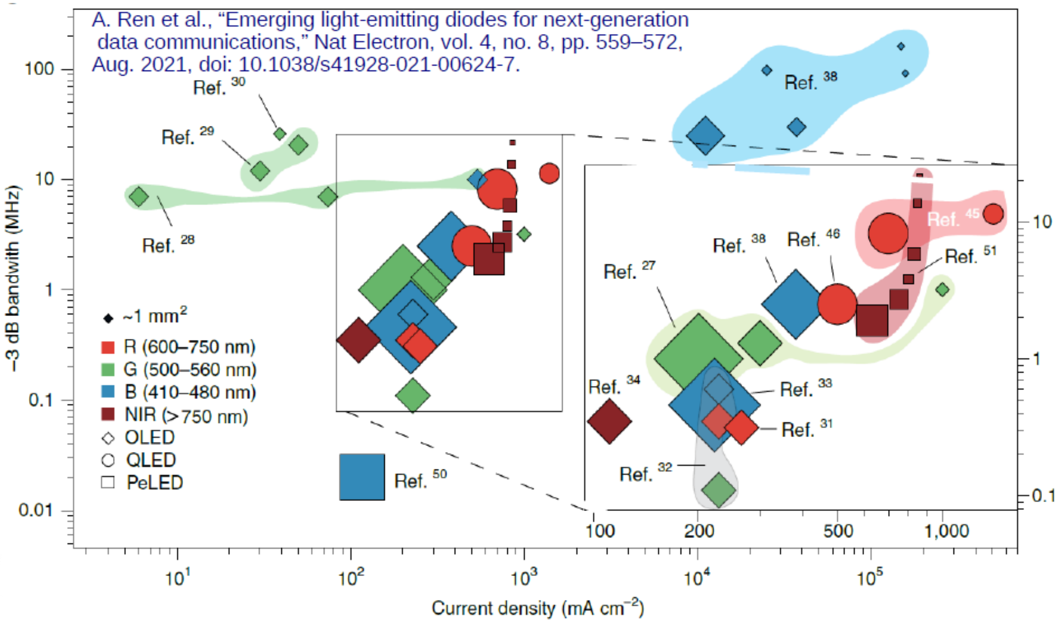
Outline

1. Context
2. Design, fabrication and characterisation of high-speed OLEDs
3. Implementation in high-speed transmission
4. On-going ANR DEµS project
5. Conclusions & Perspectives

1. Context

- **Very High-Speed Optical wireless communication with LED**
  - Recent research on LED-based communications for high speed communications mainly focused on Gallium-Nitride micro-LED devices
  - For a long time, organic LED (OLED) were seen as “slow”
  - But recently, recent works show that micro-OLED could prove to be as fast as their GaN counterparts



A. Ren et al., “Emerging light-emitting diodes for next-generation data communications,” Nat Electron, vol. 4, no. 8, pp. 559–572, Aug. 2021, doi: 10.1038/s41928-021-00624-7.

- **Organic LED brings several advantages and benefits…**
  - Lower manufacturing costs and energy needs (30 clean rooms steps)
  - Shorter time-to-market
  - Lower carbon footprint
  - Easier heterogeneous integration on numerous substrates

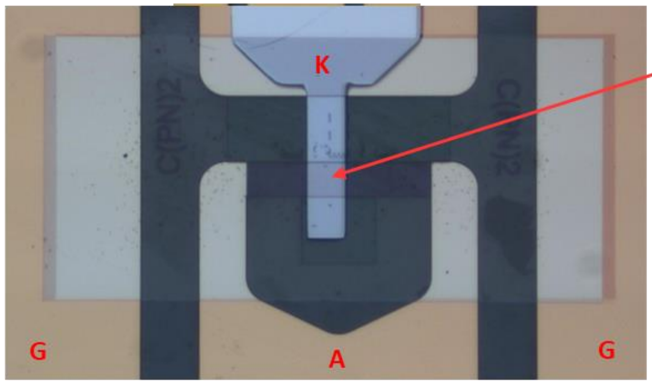
2. Design and fabrication of high-speed OLEDs

- **Different substrates for fabrication**
  - Glass (Bottom emission)
  - Silicon (Top emission)

- **Fabrication in five phases**
  - Etching – Structuration of anode, cathode
  - Metallisation – Minimize resistive effects
  - Resin isolation – Isolate the organic layers
  - Thermal vapour deposition – Deposition of organic materials
  - Atomic layer deposition – Encapsulation of Al2O3

- **OLED versus High-speed OLED**
  - Small active area (short electrical time constant)
  - Coplanar waveguided electrodes
  - Short fluorescence lifetime

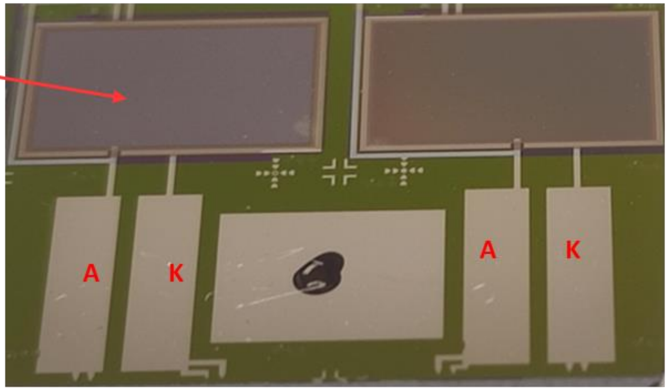
High speed CPW OLED of 200 µm² active area (Glass)



Active area

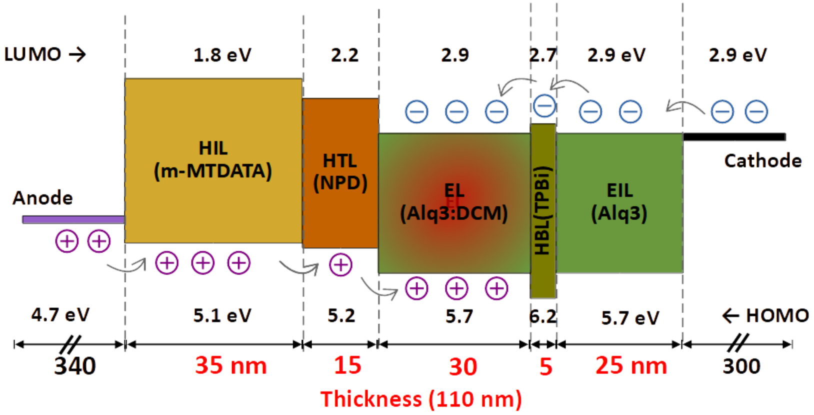
Fabricated at USPN-LPL

OLEDs of 0.44 cm² active area (Silicon)



Fabricated at CEA-DOPT

Organic heterostructure of an OLED



[1] A. C. Chime et al, "Electrical modelling and design of ultra-fast micro-OLED with coplanar wave-guided electrodes in ON-OFF regime," Organic Electronics, vol. 56, pp. 284–290, May 2018.

Dynamical OLED model based on small signal analysis

- Organic laser diode rate equations [2]

Variation of Current $I(t)$	$\frac{dI(t)}{dt}+\left(1+\frac{R_d}{R_{S1}+R_{S2}+R_{meas}}\right)\frac{1}{R_d C}I(t)=\frac{1}{R_{S1}+R_{S2}+R_{meas}}\left[\frac{dV_E(t)}{dt}+\frac{1}{R_d C}V_E(t)\right]$
Polaron density N_p	$\frac{d}{dt}N_P=\frac{I(t)P_0}{eAd}-\gamma N_P^2$
Singlet N_s and triplet density N_t	$\frac{d}{dt}N_S(t)=\frac{1}{4}\gamma N_P^2(t)-(\kappa_S+\kappa_{ISC})N_S(t)$ $\frac{d}{dt}N_T(t)=\frac{3}{4}\gamma N_P^2(t)+\kappa_{ISC}N_S(t)-\kappa_T N_T(t)$
Photon density P_{H0}	$\frac{d}{dt}P_{HO}=\beta_{sp}\kappa_S N_S-k_{cav}P_{HO}$

- Small signal analysis consideration: $N_x=N_{x0}+\delta N_x \exp^{j\omega t}$
- Transfer function of OLED:

$$\frac{\Delta P_{H0}}{\Delta V}=\left[\frac{\beta_{sp}\kappa_S\tau_{cav}}{1+j\omega\tau_{cav}}\right]\times\left[\frac{1}{2}\frac{\tau_{sp}}{1+jw\tau_{sp}}\right]\times\left[\frac{1}{2eAd}\times\frac{1}{1+jw\tau_{pi}}\right]\times\left[\frac{1}{R+R_d}\times\frac{1+jw\tau_{iv2}}{1+jw\tau_{iv1}}\right]$$

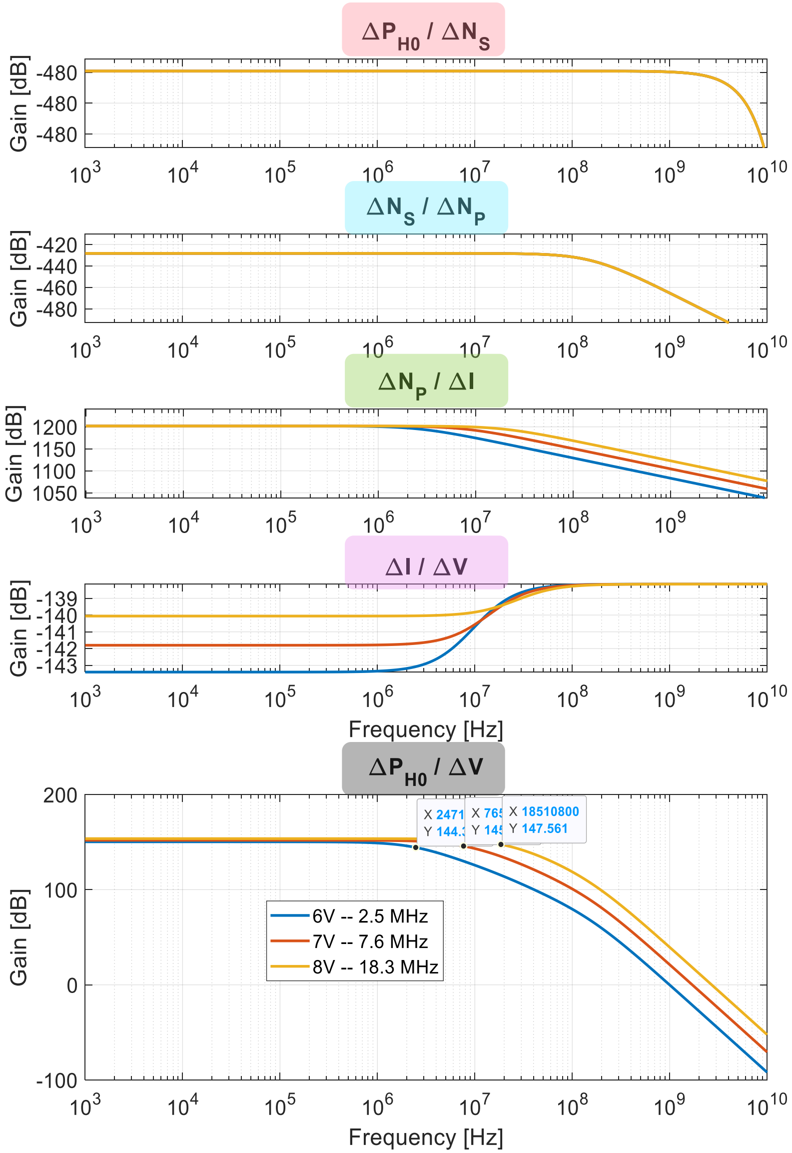
- Time constants:

$$\tau_{sp}=\frac{1}{\kappa_S+\kappa_{ISC}}$$

Singlet lifetime K_s

$$\tau_{pi}=\frac{1}{2\gamma\sqrt{\frac{1}{\gamma}\frac{1}{eAd}\frac{1}{R+R_d}V_{E0}}}$$

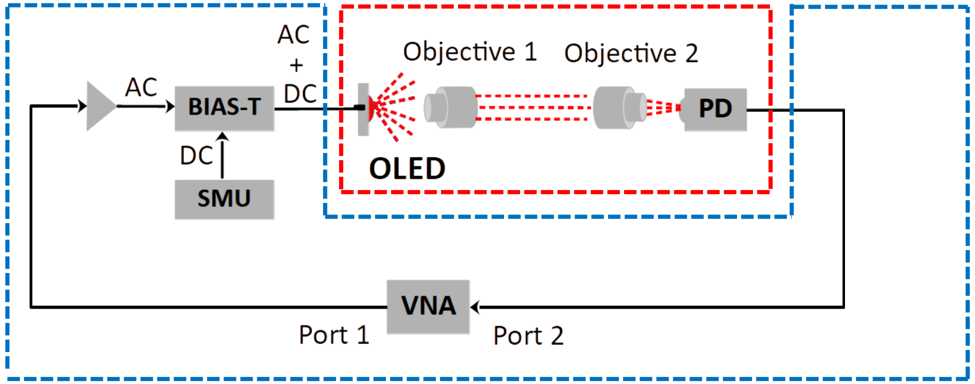
Bias voltage V_{E0}
OLED area A
OLED thickness d



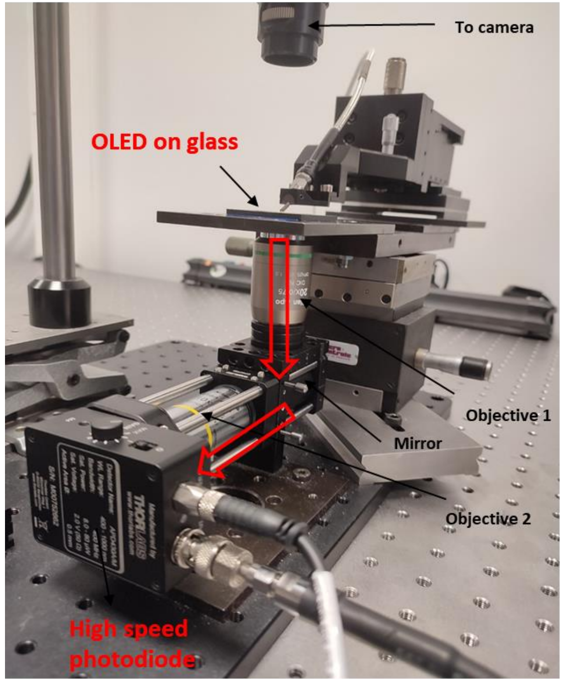
[2]. Ouirimi, A. et al. "Threshold estimation of an organic laser diode using a rate-equation model validated experimentally with a microcavity OLED", Organic Electronics 97, 106190, 2021
[] Mohamed Nihal Munshi, Alex Chime, Alexis P.A. Fischer, Luc Maret, Benoit Racine, Mahmoud Chakaroun, "Small signal analysis in OLED", to be submitted

Optical setups for bandwidth analysis

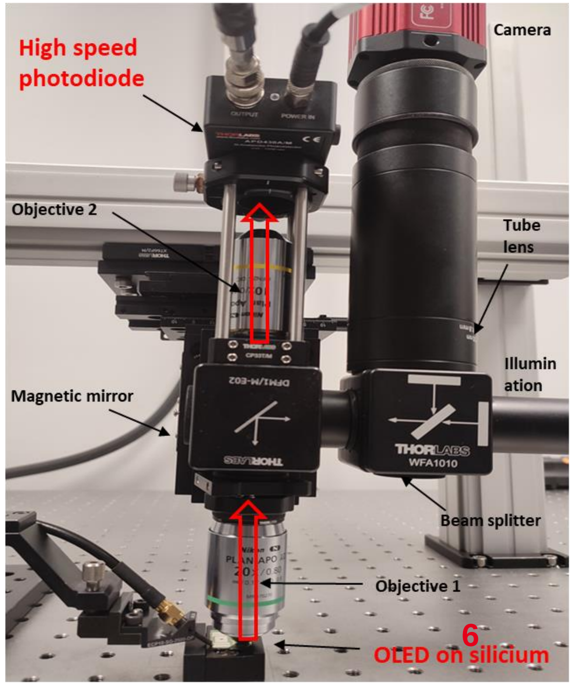
- Optical section for light collimation onto Photodetector (PD)
    - Maximize the light flux (Numerical aperture)
    - Optimize the image size on PD (Magnification)
- Electrical section for RIN characterization
    - VNA Port 1 → Frequency-sweep RF signal
    - Bias-tee for coupling BIAS and RF
    - OLED modulation (Electrical-to-Optical)
    - High speed photodiode (Optical-to-Electrical)
    - VNA Port 2 → Measurement of Rx amplitude and phase



Bottom emission setup



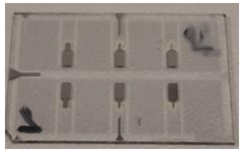
Top emission setup



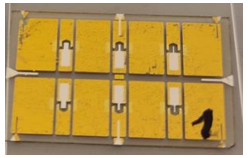
Heterostructure impact on bandwidth

- **Effect of the <u>electrodes</u>, <u>emitting layer</u> and <u>hole blocking layer</u> (500 µm² CPW OLED on glass)**

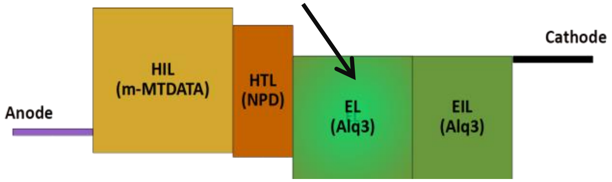
Substrate non-metallized



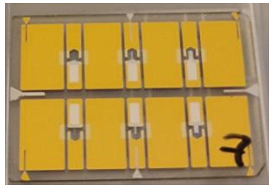
Substrate metallized



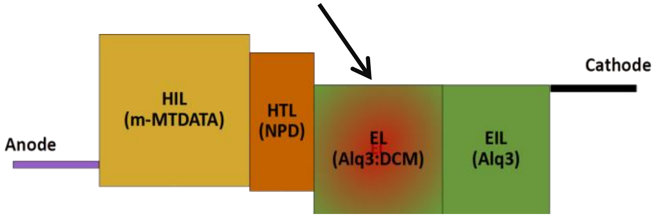
Alq3 as emitting layer (without HBL)



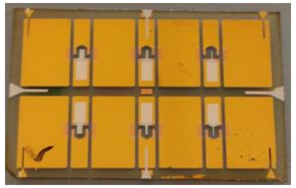
Substrate metallized



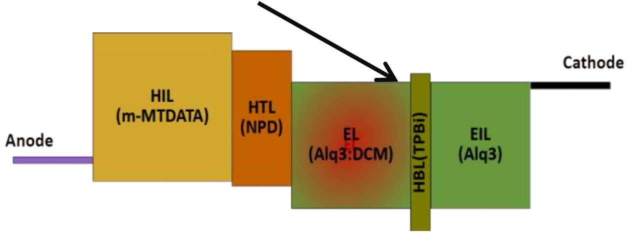
Alq3:DCM as emitting layer (without HBL)

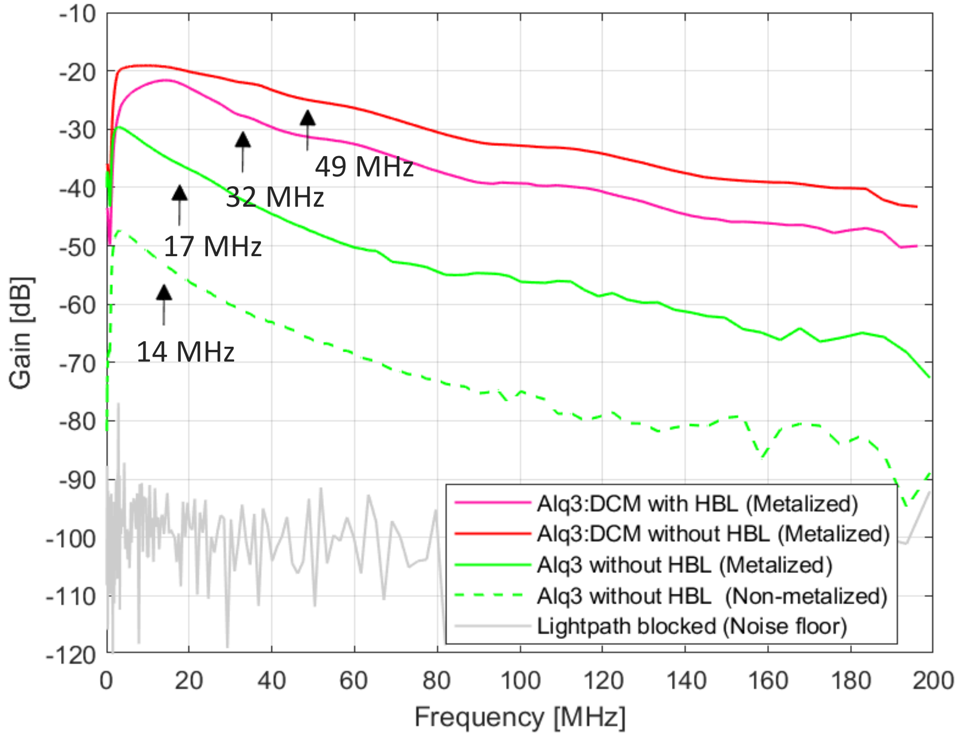


Substrate metallized



Alq3:DCM as emitting layer (with HBL)





- Bandwidth increased from 14 MHz to 17 MHz by metallizing the CPW electrodes (RC time constants - τ_{iv1}, τ_{iv2})
- Increased from 17 MHz to 49 MHz by using red emitting layer w/o HBL (Spontaneous emission lifetime τ_{sp})

Active area impact on bandwidth

Effect of the OLED active area (500 µm², 200 µm² and 100 µm² CPW OLED on glass)

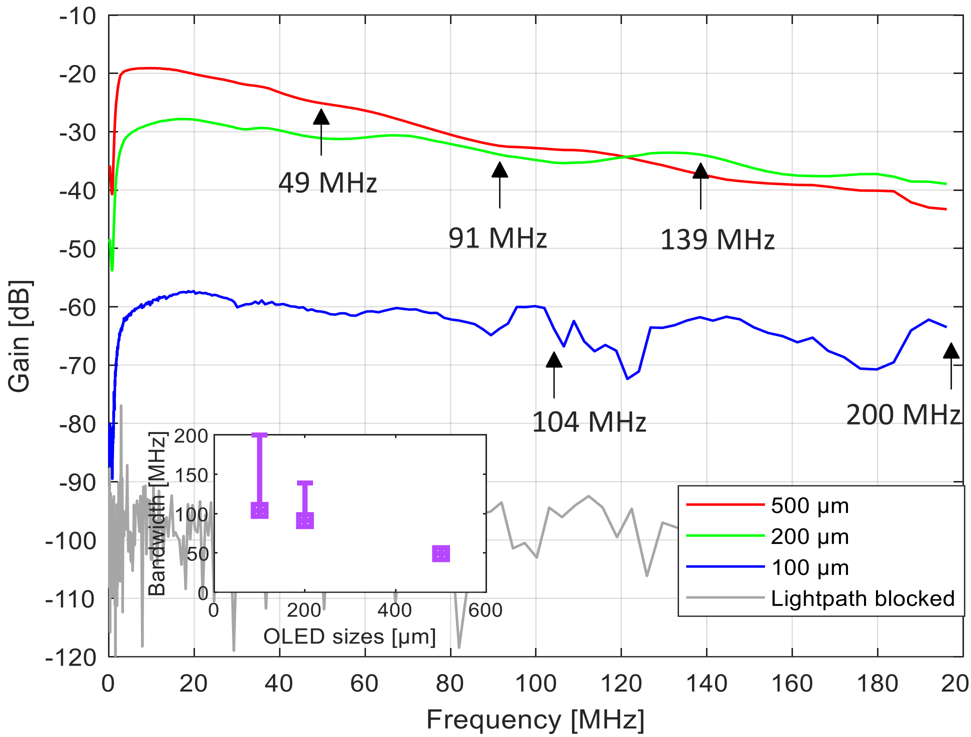
- Electro-to-optical bandwidth relation [3]:

$$f_{3dB} = \frac{1}{2\pi C}\left(\frac{1}{Rs} + \frac{1}{Rd}\right)$$

C → Capacitance

Rs → Serial resistance

Rd → Dynamic resistance



- Bandwidth increased from 49 MHz for 500 µm² to 91 MHz for 200 µm² and to >200 MHz for 100 µm² (Active area)
- Bandwidth at the state of the art → 245 MHz [3]
- Resolution limited by parasitic RF emission

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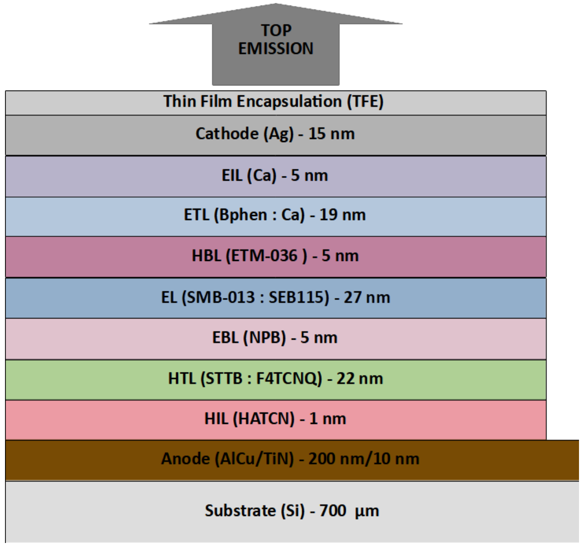
[3] K. Yoshida et al., “245 MHz bandwidth organic light-emittng diodes used in a gigabit optical wireless data link,” Nat Commun, vol. 11, no. 1, Art. no. 1, 2020.

Bias voltage impact on bandwidth

- Effect of PIN doping on the bias voltage impact (40x40 µm² non-CPW OLED on Silicon)



PIN doping in heterostructure

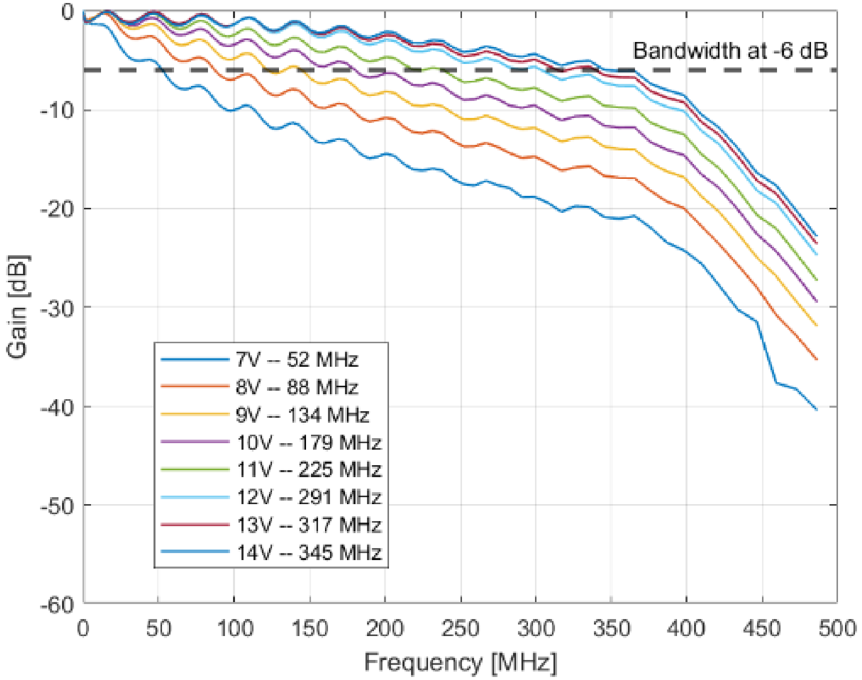
- Langevin recombination rate :

$$\gamma = \frac{e}{\epsilon}(\mu_h + \mu_e) \simeq \frac{e}{\epsilon}\mu_0 \exp\left(\frac{-Ea}{kT}\right)\exp\left(\delta\frac{\sqrt{F}}{kT}\right)$$

- Poole Frenkel law :

$$\mu(t) = \mu_0 \exp\left(\frac{\sqrt{V_D(t)}}{V_0}\right)$$

V_D → Voltage applied across OLED



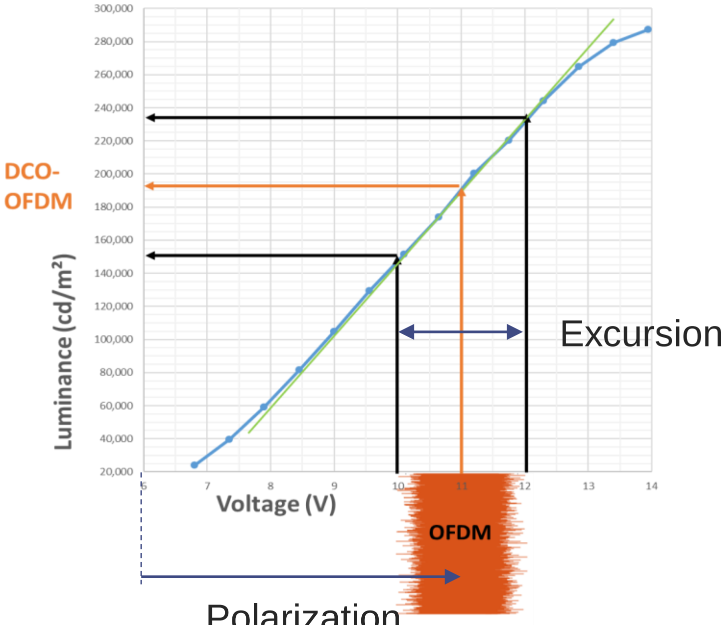
- Bandwidth increased from 52 MHZ to 345 MHz when bias voltage is increased
- Bandwidth beyond the state-of-the-art (245 MHz [3])
- Bias voltage increased → Mobility increase exponentially → Bandwidth increase (paper submitted [4])

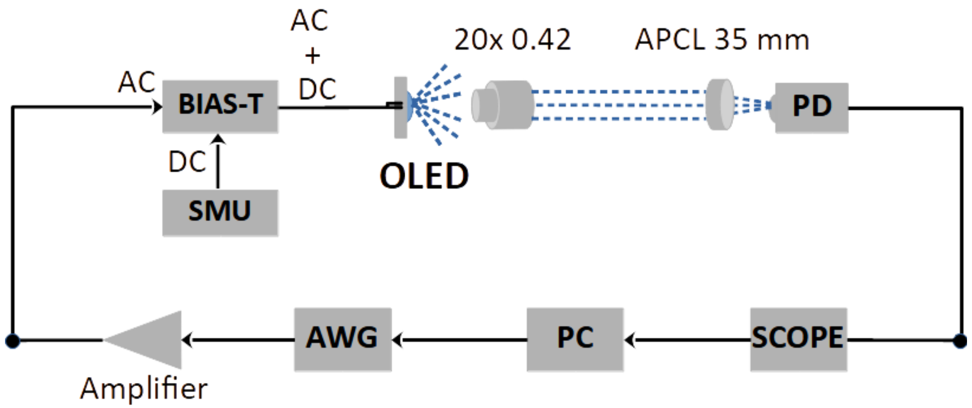
[3] K. Yoshida et al., “245 MHz bandwidth organic light-emittng diodes used in a gigabit optical wireless data link,” Nat Commun, vol. 11, no. 1, Art. no. 1, 2020.

[4] Mohamed Nihal Munshi, Nixson Loganathan, Alexis P.A. Fischer, Luc Maret, Mahmoud Chakaroun, Benoit Racine, “Relative Intensity Noise measurement of high-speed µ-OLEDs towards visible light communication”, submitted to Organic electronics.

3. Implementation in high-speed transmission

- **Using micro-OLED on Silicon:**
  - Primary designed for micro-display
  - Non-CPW electrodes structures
- **Transmission with multi carrier modulation: Direct Current Optical – OFDM (DCO-OFDM)**
  - High spectral efficiency
  - Benefit from high bandwidth using a high DC bias
- **Use of AWG, Amplifier, Scope and PC for transmission**
  - AWG for transmission, Scope for acquisition and PC for pre-processing and post-processing



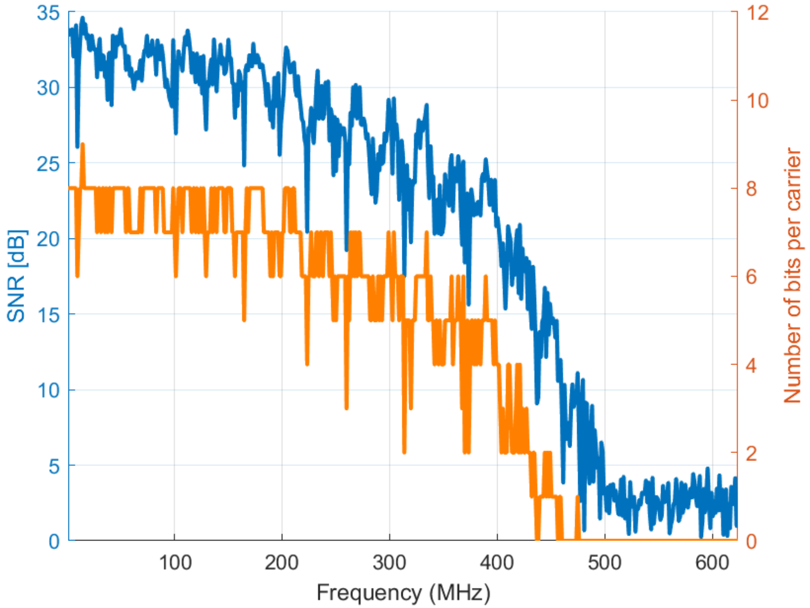


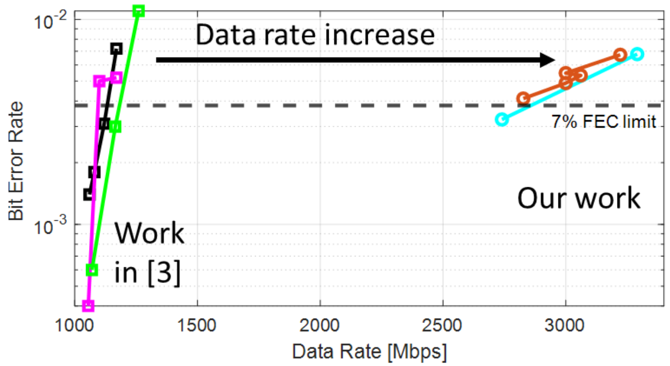
Transmission with OLED using DCO-OFDM

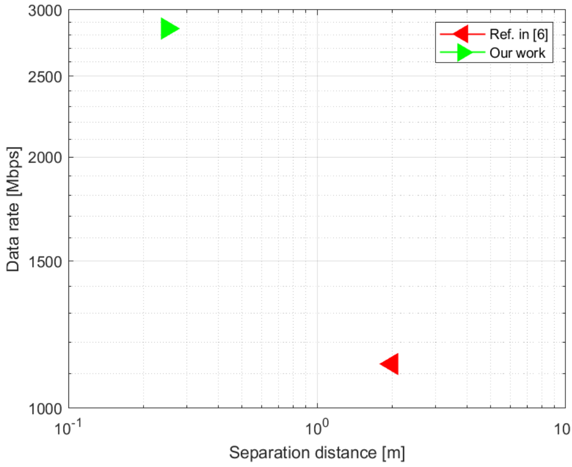
- Best performance reached on a square 40x40µm² blue OLED

- Pilot-based transmission for bit and power loading algorithm
  - Modulation bandwidth : DC-500 MHz (Bias V_{dc} =12 V)
  - Up to 35dB of SNR
  - Bit loading: up to 9 bits per sub-carrier

- **Data rate reached: 2.85 Gb/s at BER=3.8e-3**







[3] K. Yoshida et al., “245 MHz bandwidth organic light-emittng diodes used in a gigabit optical wireless data link,” Nat Commun, vol. 11, no. 1, Art. no. 1, 2020

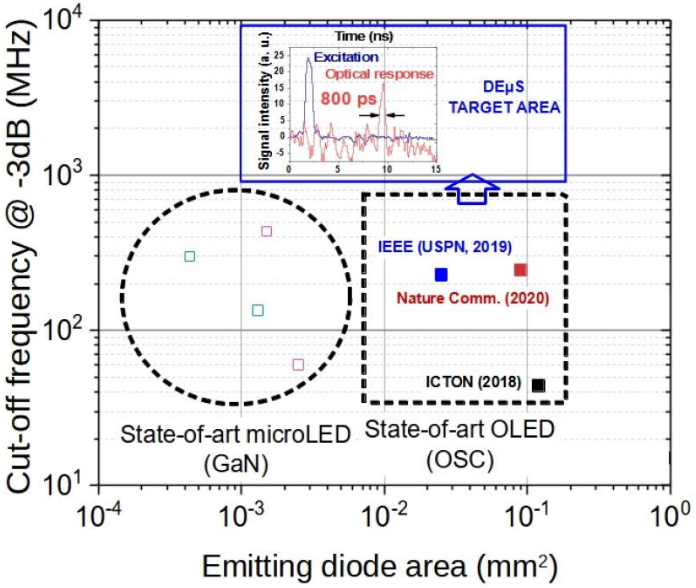
[5] Mohamed Nihal Munshi, Luc Maret, Benoit Racine, Alexis P.A. Fischer, Mahmoud Chakaroun, Nixson Loganathan, “Reaching 345 MHz bandwidth and 2.85 Gb/s using a blue 40 µm OLED under submission to IEEE Photonic Technology Letters“.

4. ANR DEµS project

- French national project between Univ. Sorbonne Paris-Nord and CEA-Leti

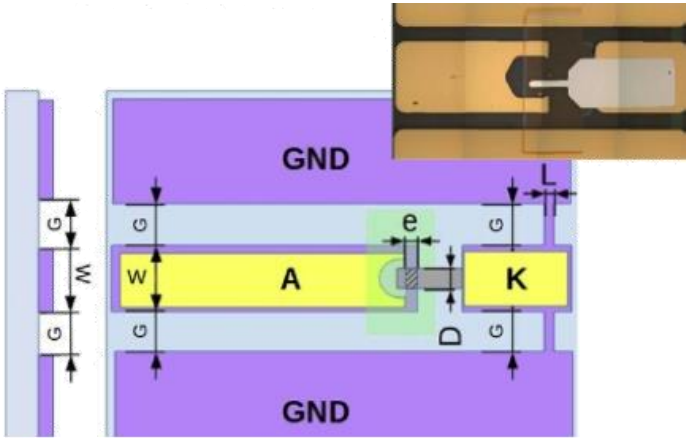
- Main objectives:
  - Design of Sub-ns High-Speed Organic Light Emitting Diodes on Silicon

  - Implementation into ultra-high speed communications



4. ANR DEμS project

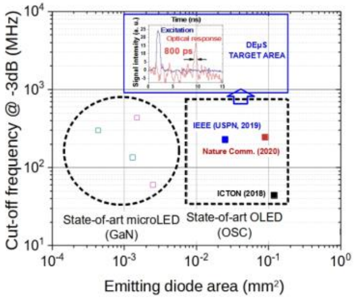
- **Research at device level**
  - Screening of high-speed emitting molecules running in the sub-ns range
  - Monolithic integration on silicon
  - CoPlanar Waveguided (CPW) electrodes to ensure high-speed electronic response and adapted impedance
  - Atomic Layer Deposition (ALD) encapsulation: allows for waveguide coupling



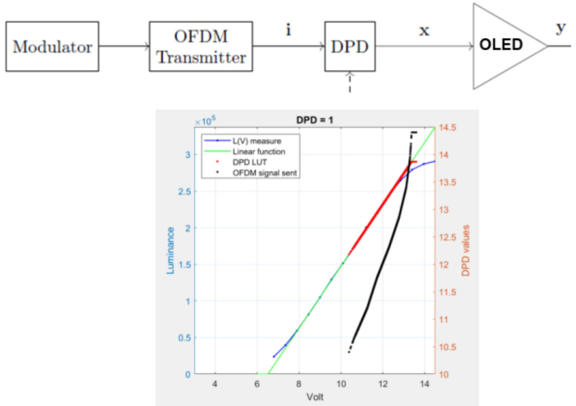
- **Innovation at transmission level**
  - Different single micro-OLED designs for performance analysis
  - Fabrication of inline and squared matrices for enhanced system performance:
    - Range increase
    - Integration of DC-less modulations (M-PAM,…) with future integrated CMOS current drives

Conclusions & Perspectives

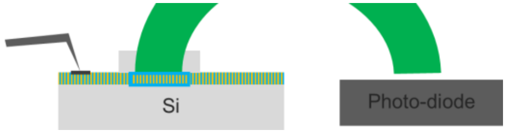
- **CONCLUSIONS:**
  - Fabrication of high speed OLEDs based on a novel technology
  - Analysis of heterostructure layer impact on bandwidth
  - Analytical model to infer OLED’s characteristics
  - Bandwidth of 345 MHz and data rate of 2.85 Gb/s
  - With further improvements, OLEDs could compete with GaN LEDs

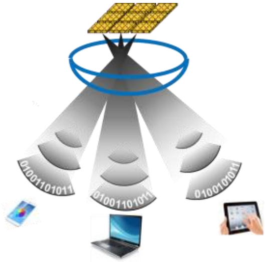


- **WORK IN PROGRESS**
  - Improve transmission performance
    - Linearization of OLED characteristics by Digital Pre-Distortion (DPD)
    - Reduction of Peak to average power ratio (PAPR)
  - CPW High Speed OLEDs on silicon (ANR-DEµS)
  - Transmission on matrices of CPW OLED on Silicon (ANR-DEµS)



- **PERSPECTIVES:**
  - Targeting bandwidth up to 1 GHz and data rates up to 10 Gb/s
  - Going step further into integration:
    - Integrated emitter/receiver optical front-ends
    - Integrated process for optical beamforming
  - Positioning µOLED in terms of rate, pJ/bit and Tb/mm²





THANKS FOR YOUR ATTENTION