Quantum Rods LEDs: A way to achieve LED Efficacy of >200 lm/W

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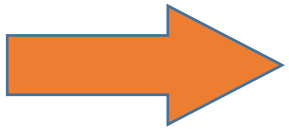
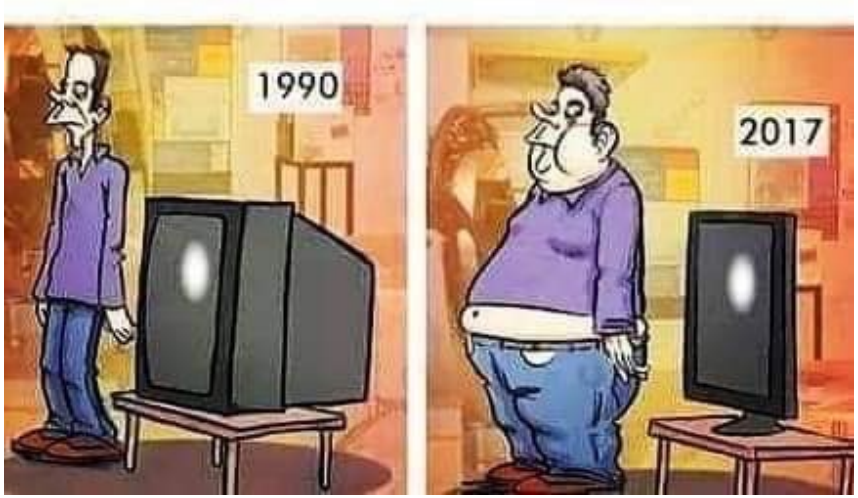
香港科技大學
THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

In Last 30 Years!



1990 - 2017



Next 30 Years?

Latest Trend in the Display Technology

LG OLED Canyon

146” 4KHDR Samsung QDLED

Speakers in the display

AR/VR displays/ high resolution display

Antenna/LCDs

Medical interactive displays/scanner

Power consumption is one of the biggest issue. The display efficiency is limited to 3-5% only!

LCD is the market leader with ~70% market share.

Power Consumption @ Smartphone: LCD

Simple content with text and graphics.

Wi-Fi

Component	Consumption (mW)
GSM	80
CPU	60
Wi-Fi	100
Graphics	80
Rest	55
LCD- (backlight +LCD)	480 (**419**+61)
Total (backlight consumption %)	845 (**49.6%**)

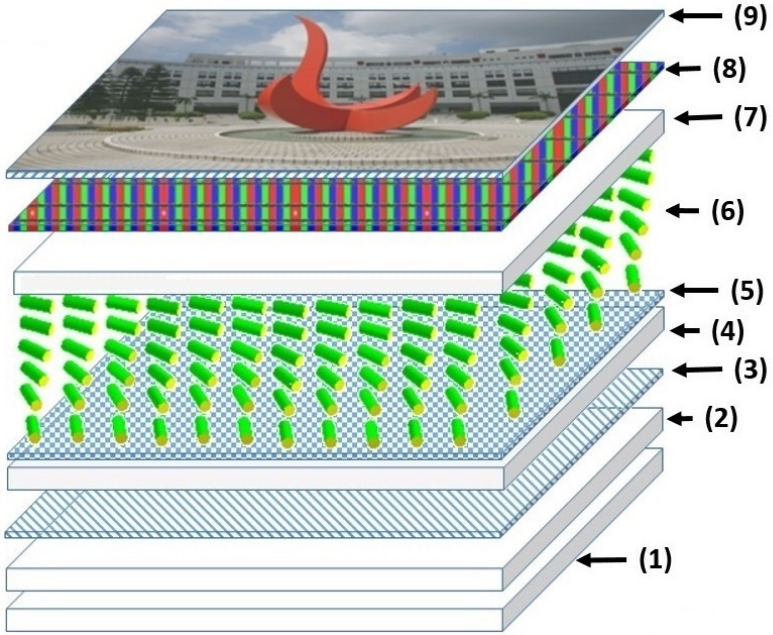
Cellular

Component	Consumption (mW)
GSM	360
CPU	55
Wi-Fi	10
Graphics	80
Rest	55
LCD- (backlight +LCD)	480 (**419**+61)
Total (backlight consumption %)	1040 (**40.2%**)

- In 2019, we had 6.61 million smartphone users in Hong Kong.
- If we consider average 2.5W for displays only, then it is going to be a significantly big number for the power consumption.
- On an average, in Hong Kong we consume 400-600 Terajoule/year of energy for consumer displays only.

https://www.usenix.org/legacy/event/usenix10/tech/full_papers/Carroll.pdf

Polarizers and color filters are Critically Important for light efficiency of LCDs!



	Efficiency and Brightness of the LCD			
		Conventional LCD/QDEF		LCD with NREF	
	Components	Efficiency, %	Brightness, %	Efficiency, %	Brightness, %
1	Backlight	100.0	100.0	100.0	100.0
2	Light diffusive films	75.0	75.0	75.0	75.0
3	polarizers	45.0	33.8	70.0	52.5
4	Glass	95.0	32.1	95.0	49.9
5	TFT active matrix	65.0	20.8	65.0	32.4
6	LC matrix	85.0	17.7	85.0	27.6
7	Glass	95.0	16.8	95.0	26.2
8	Color Filter	30.0	5.0	30.0	8.3
9	Analyzer	95.0	4.8	95.0	7.9
	Final Image		4.8		7.9
	Color Triangle		>100 NTSC		>100 NTSC

- In 2019, we had 6.61 million smartphone users in Hong Kong.
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- On an average, in Hong Kong we consume 400-600 Terajoule/year of energy for consumer displays only

- **We can increase the optical efficiency > 20%.**

W. C. Yip, H. C. Huang, and H. S. Kwok. "Efficient polarization converter for projection displays", App. Opt. ,, 36, 6453, 1997.
A. K. Srivastava, V. Chigrinov and H. S. Kwok, SPIE newsroom Article", 2014. DOI: 10.1117/2.1201412.005595
E. Ploshnik , A. Salant , U. Banin , R. Shenhar, Adv. Mater., 22, 2774–2779, 2010.
A. K. Srivastava, W. Hu, V. G. Chigrinov, A. D. Kiselev and Y. Q. Lu, Appl. Phys. Lett., Vol. 101, 031112, 2012.
Z. Luo, Y. Chen, and S. T.Wu, Wide color gamut LCD with a quantum dot backlight, Opt. Express 21 (22), pp. 26269–26284, 2013.

QDEF Films Market

Asus Zenbook NX500

And Many more!
QD materials market size is over 7bUS$.

"We believe quantum dot is the future of display technology," ***Joe Stinziano***, executive vice president of the consumer business division at Samsung Electronics America, Ridgefield Park, NJ.
http://www.xconomy.com/new-york/2016/01/15/the-next-phase-of-the-tv-tech-battle-quantum-dot-vs-oled-display/#

http://www.digitaltrends.com/home-theater/lg-to-unveil-new-quantum-dot-tvs-at-ces/

Low Optical Efficiency of LCDs ?

- ***Polarization Losses: how can we improve it?***
  - *Polarized emission from **Photoaligned Quantum rods** can help here.*
  - *Quantum rods for lighting and displays*
- ***Color Filter Losses:***
  - ***Remove the color filters?***
    - *Field Sequential Color displays using ferroelectric liquid crystals.*

      Key Challenge: Fast response of the Liquid crystals
  - ***Change it to photo-luminescence type color filter?***
    - *Photo-luminescence type color filter using downconverting materials in pixels.*

      Key Challenge: Pixelation

Quantum rods offer better efficiency and saturated color

Emitting Material	Methodology	CCT (K)	Color gamut(%)	LE (lm/W)	Year	Ref
CdSe//ZnS/CdSZnS	Liquid type QD	-	-	103	2018	Optica. 2018, 5, 793
CsPbBr3CsPbBr1.2I1.8	Liquid type perovskite	5516	122	51	2019	Phot. Res. 7, 579.
RbNa(Li3SiO4)2: Eu2+	Narrow bandwidth phosphor	5196	113	111	2019	Adv. Func. Mat. 1901988.
Cs3Mn0.96Zn0.04Br5 K2SiF6:Mn4+	Narrow bandwidth phosphor	6723	101	108	2019	*J. of Mat. Chem. C.* **2019**, 7, 11220
CdSe/ZnxCd1-xS	Gradient alloyed QRs	8909	122	115	2021	Small, 17, 2004487.
QD/SBA-15	Matrix reduces reabsorption	6500	118	136.7	2021	ACS Nano, 15, 550-562

Theory: When you know many things, but nothing works!

Experiments: It works but no one knows why!

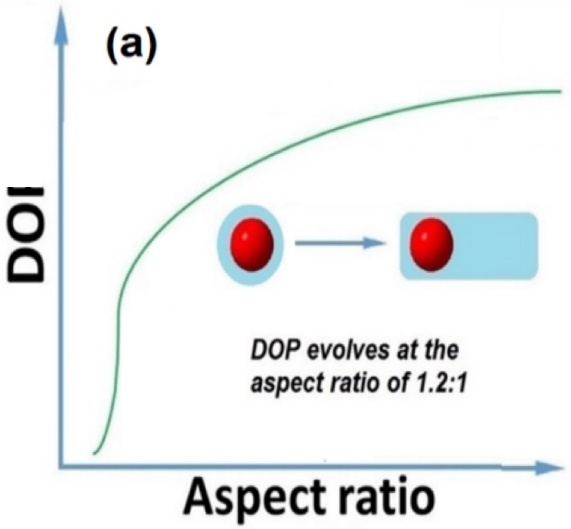
In my lab: We combine theory and experiments:

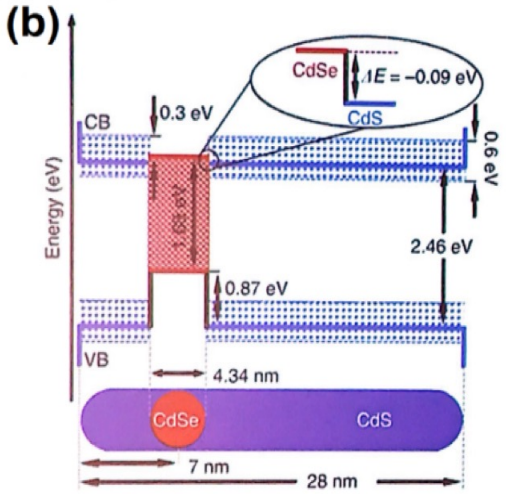
Nothing works

and no one knows why!

Quantum rods: Polarized Emission from QRs?

SCIENCE VOL 292
15 JUNE 2001

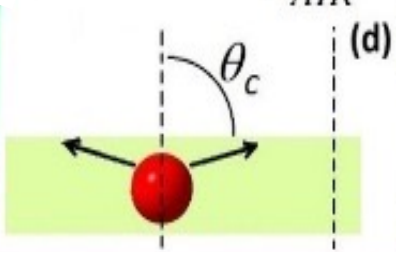


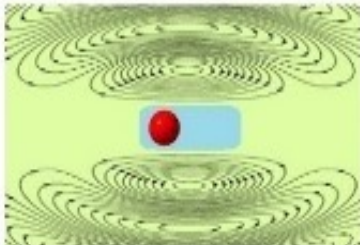


Nature Communications **4**, 2376 (2013)

Better optical coupling efficiency.

$$\sin\theta_c = \frac{n_{LCP}}{n_{AIR}}$$



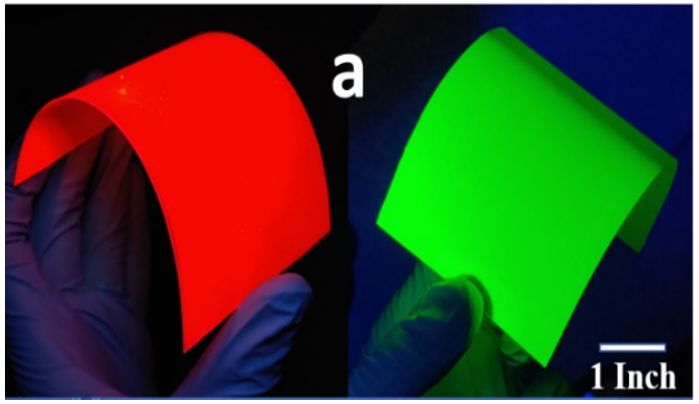


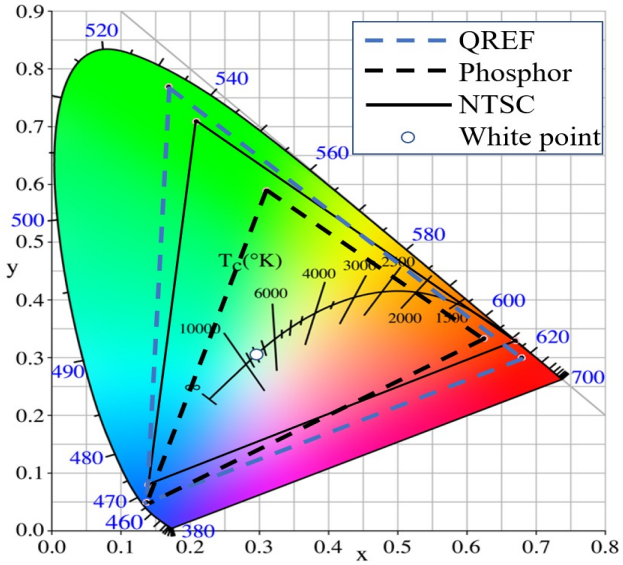
QD NR

Dipolar emission can improve the coupling efficiency, if the dipoles are assembled in plane!

ACS Nano, 2015, 9 (8), pp 7992.
J. Phy. Chem. Lett. C, 2013, 117,pp 23928.

QREF Improves the Colors and LCD Efficiency



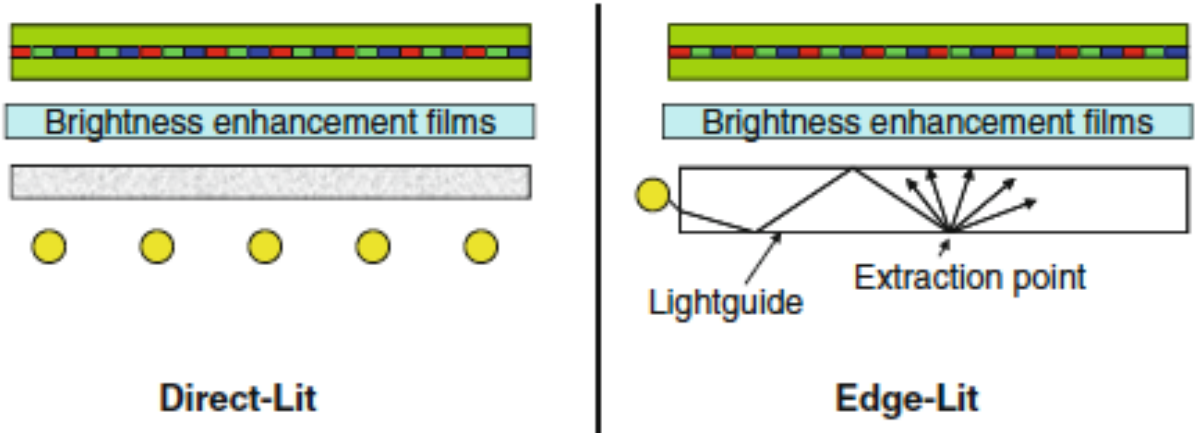


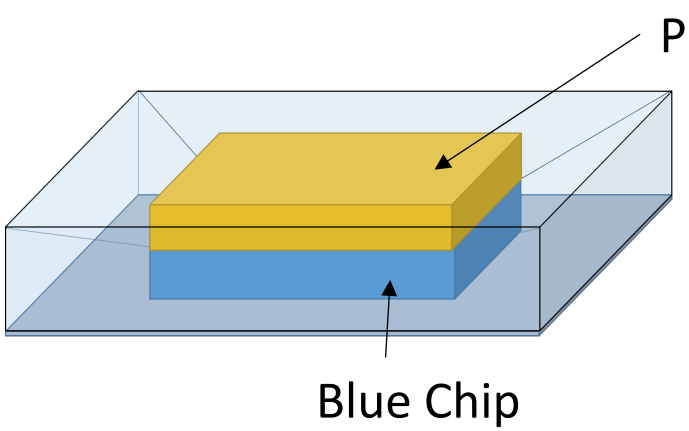
- ***Brightness : 560 Nits***
- ***Efficiency=7.8%***
- ***Color triangle 97% BT2020***
- ***Cost is still high than modern LCDs***

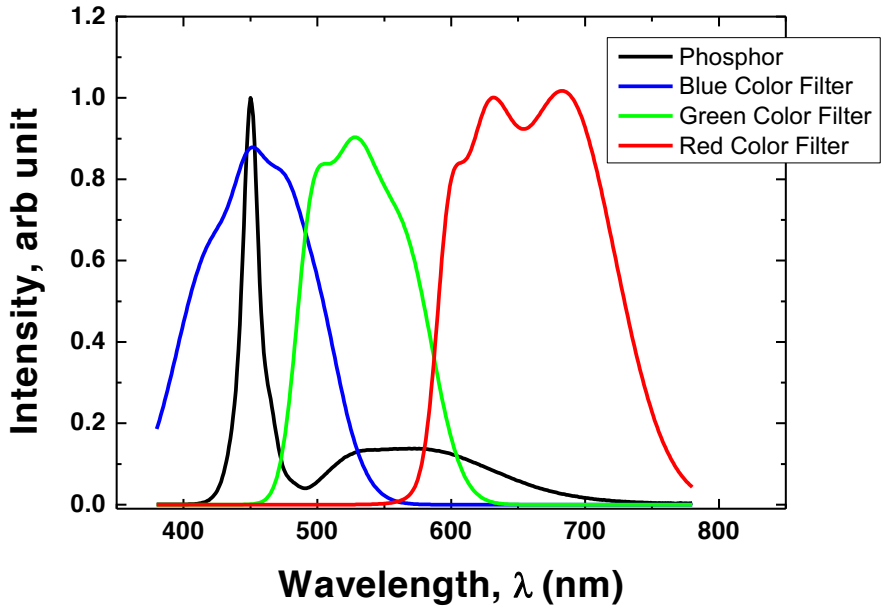
https://youtube.com/shorts/agLCBP89cqM?feature=share

Nano Research, 1-10, 2022
Nanophotonics, 10(7), 1801, 2021
Adv. Sciences. 6, 1901345, 2019.
Nanoscale, 11, 20837, 2019.
Adv. Mater. Technol. 1900695, 2019.
Adv. Fun. Mat., 180594, 2018.
Adv. Opt. Mat. 1800250, 2018.
Adv. Mat. 1701091, 2017..

LED with High Efficacy and Large Color Gamut



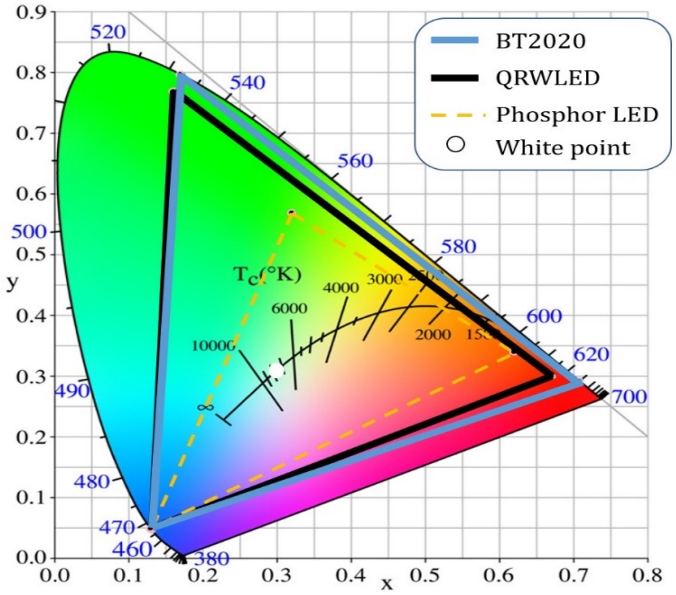


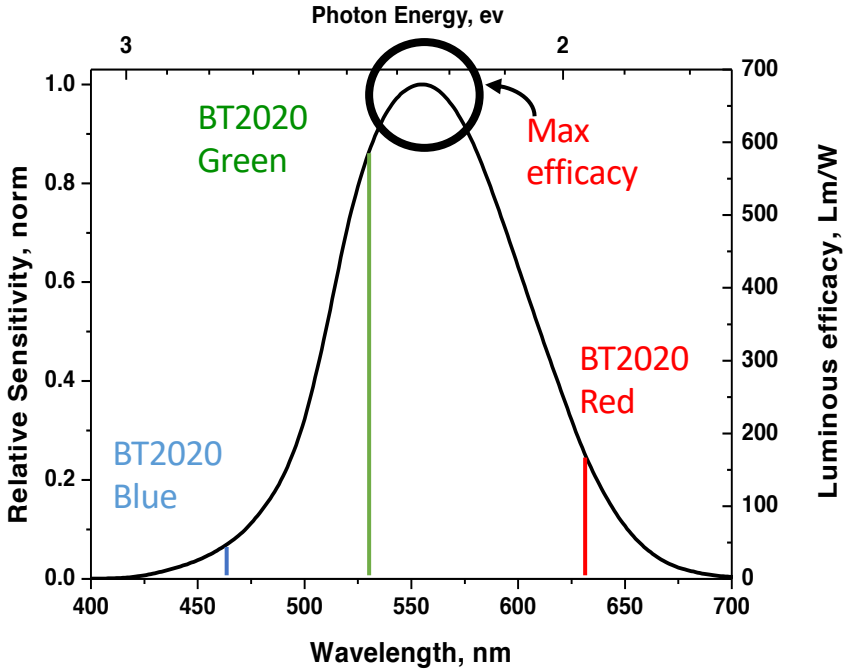


Display LED efficacy = 70-90 lm/W
Color gamut is small.

Adv. Mat., 2104685, 2021

LED with High Efficacy and Large Color Gamut

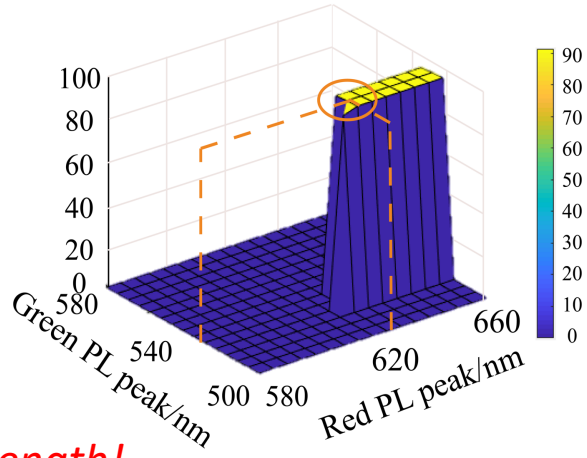




The LER (lm/Wopt) is the ratio between the luminous flux (in lumens) and the optical power of radiation (in watts, W). This metric differs from a related but distinct metric, the luminous efficacy of a source (LE, lm/W_{ele}), which is the ratio between the luminous flux and the input electrical power used to produce that luminous flux

$$\mathrm{LE} = \frac{\int_0^\infty I_e(\lambda)K(\lambda)d\lambda}{IV}$$

$$\mathrm{LER} = \frac{\int_0^\infty I_e(\lambda)K(\lambda)d\lambda}{\int_0^\infty I_e(\lambda)d\lambda}$$

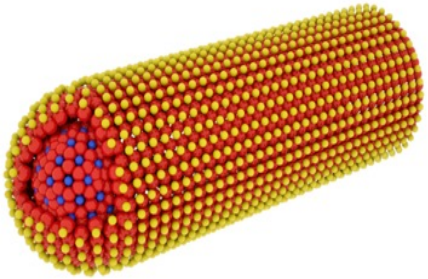


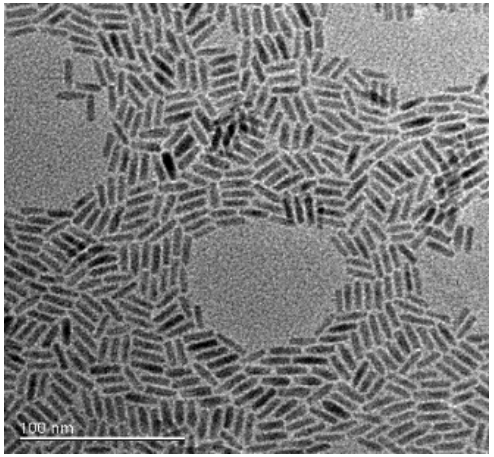
We need a precise control on the emission wavelength!

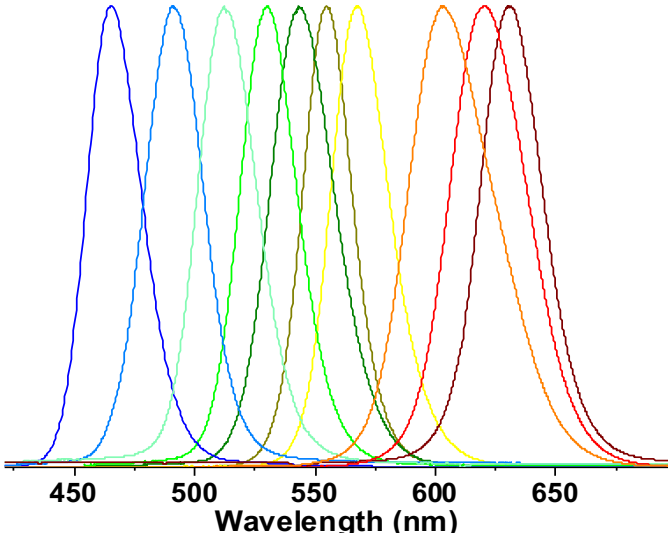
Adv. Mat., 2104685, 2021

Quantum Rods Have Better colors

Quantum Rods, Covering Full Visible Range for Display and Lighting Application



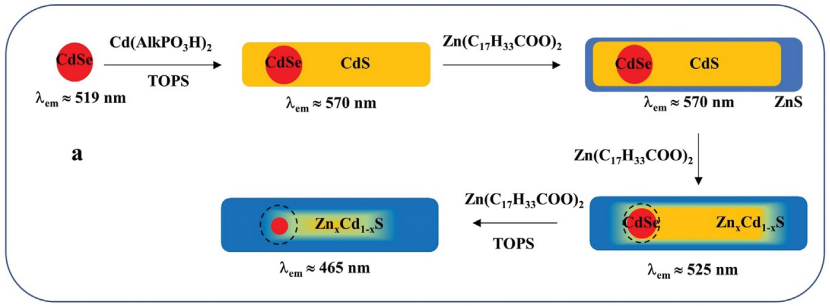


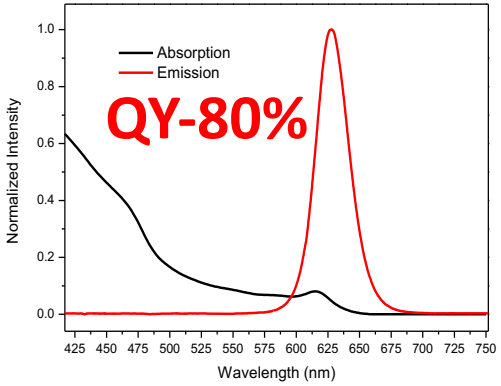


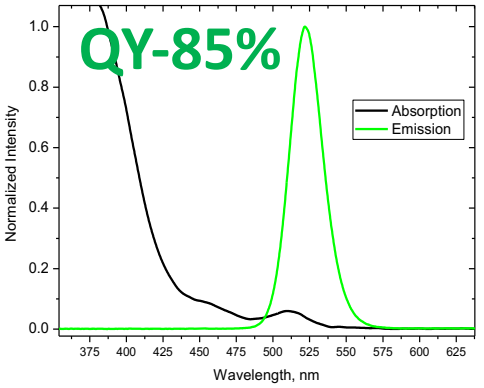
We developed a new approach to make the Quantum rods emitting in the full visible range.

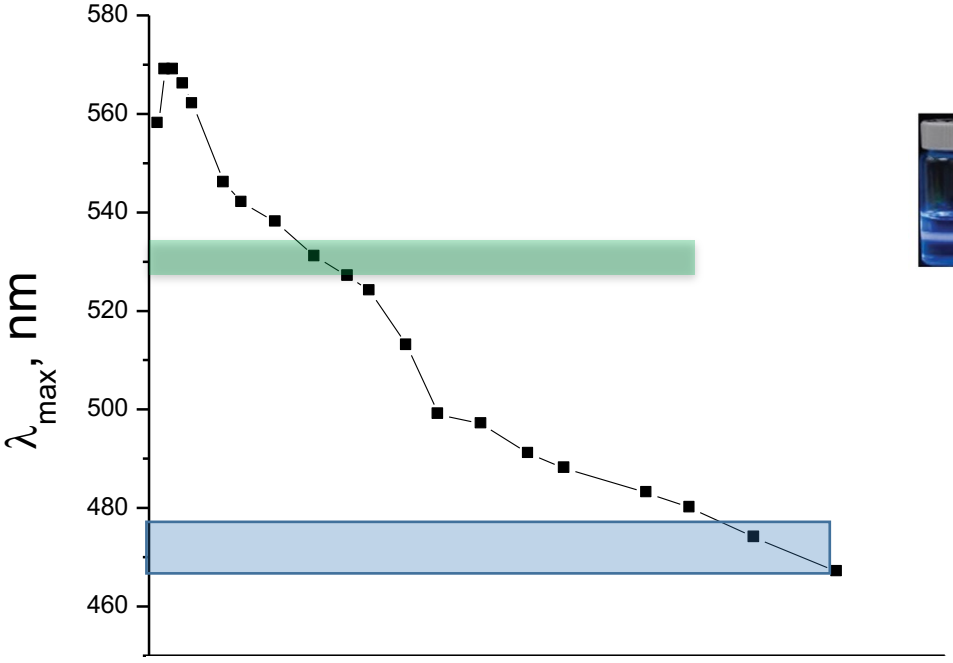
Adv. Mat., 2104685, 2021

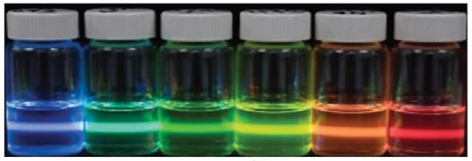
Blue Quantum Rods @2020

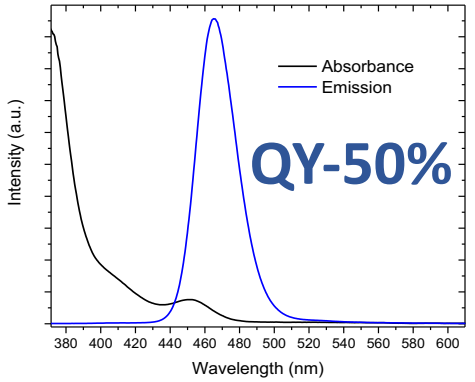


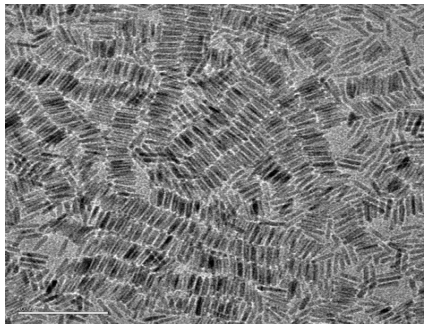


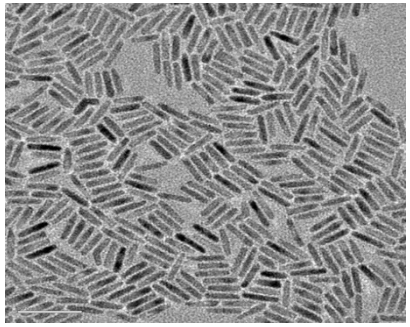








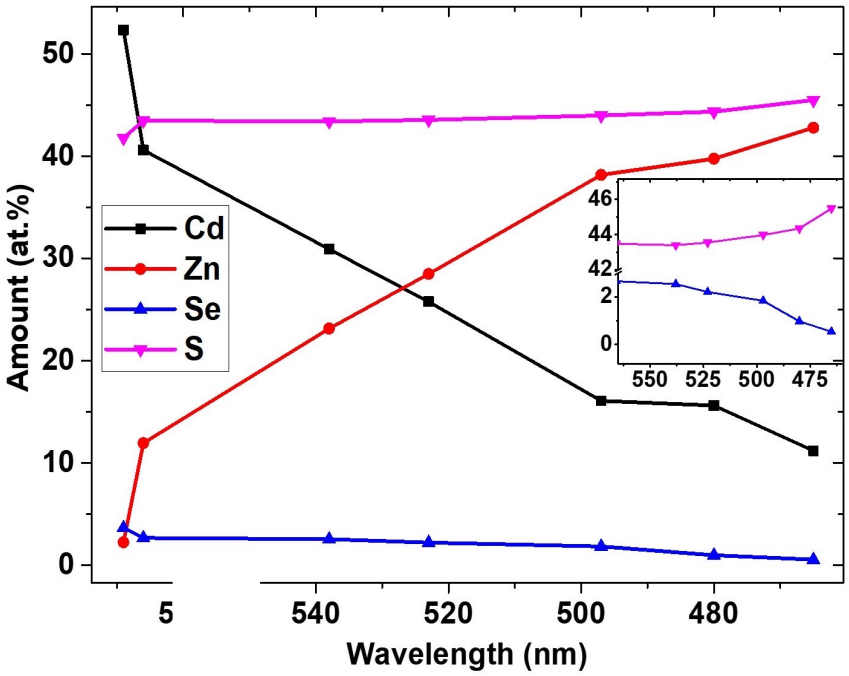


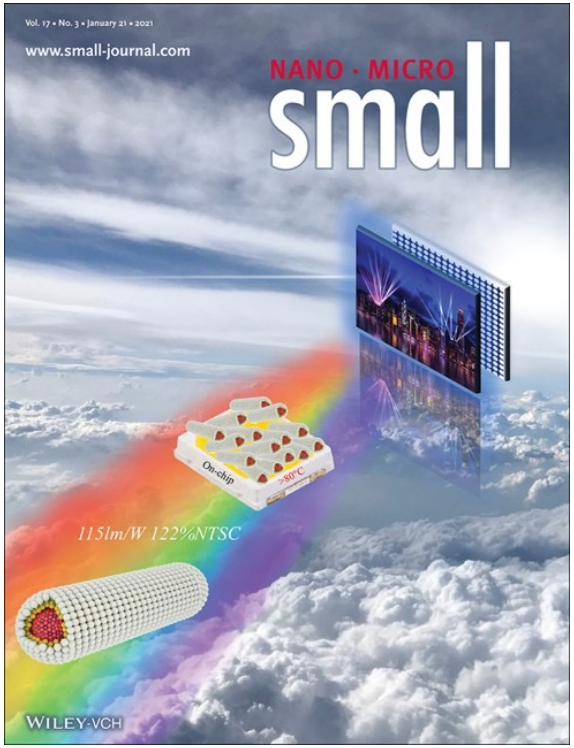


Length ~26nm
Diameter ~ 5nm
QY~50% and FWHM~27nm

Small, 2004487, 2021
Nanophotonics, 10(7), 1801, 2021

Low Cd and Thermally Stable QRs

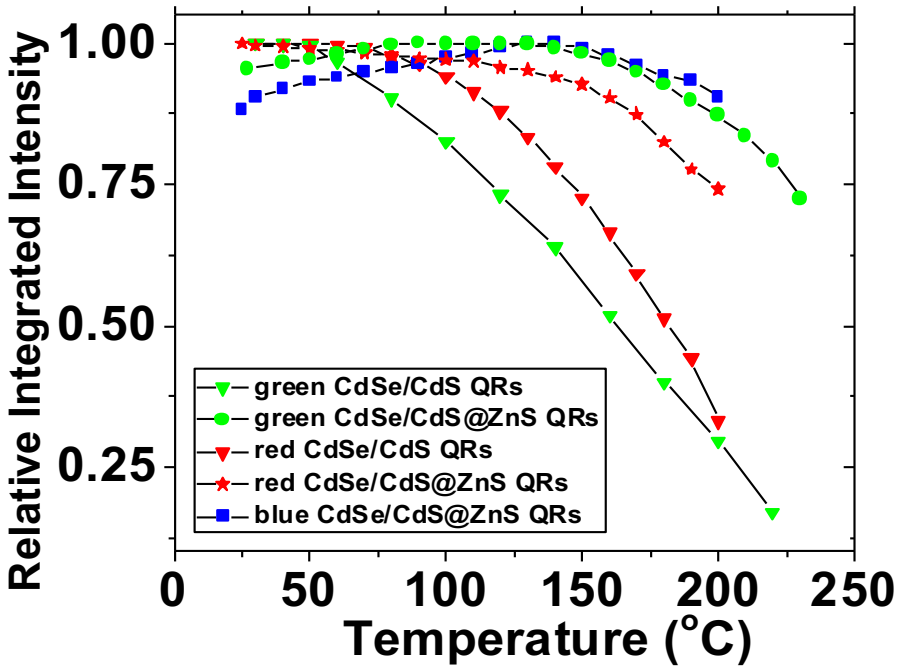


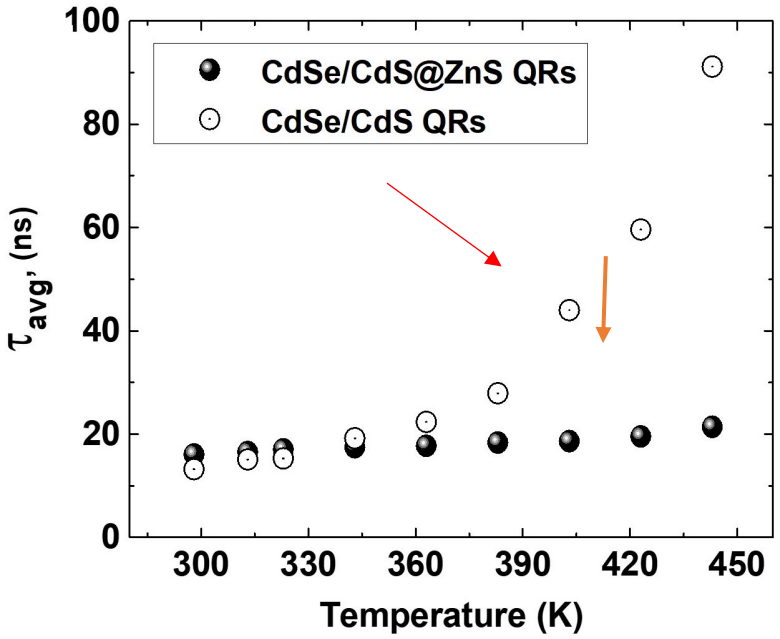


- EDX elemental analysis results plotted versus emission wavelength for the purified probes during the synthesis.
- The Cd concentration drops significantly.
- Red, Green and Blue

Small, 2004487, 2021

Low Cd and Thermally Stable QRs



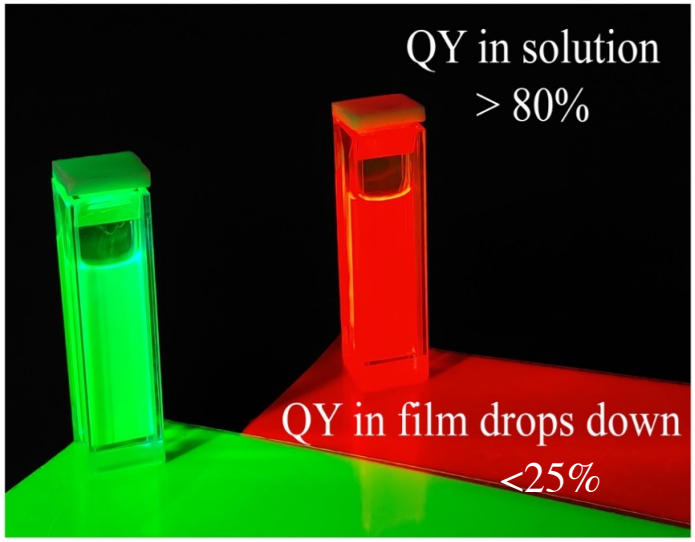


- Stable Emission till 150°C.

How about the quantum yield?

Small, 2004487, 2021

Low Quantum Yield in the Film



In closely **packed NP films**, particle to **particle energy transfer** (ET) results in severe **nonradiative decay**. Excitons are known to **diffuse via donor-acceptor ET**, which is strongly related to the interparticle distance. **FRET** leads to **more active nonradiative fast decay pathways** when **QRs are packed densely in films**.

The following equation relates the PL-QY in the film to that in solution-state with a multi-process in lifetime fitting.

$$QY_f = \frac{QY_s \times k_{rad}}{k_{rad} + k_{ET}(1 - QY_s)}$$

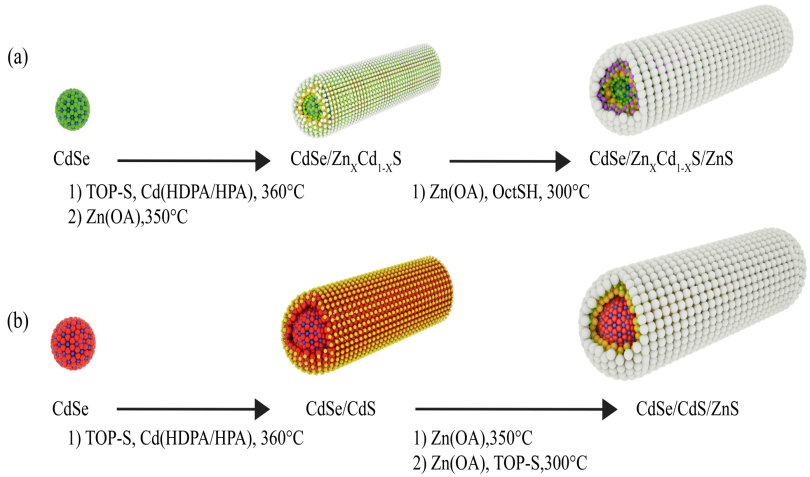
$$k = k_{rad} + k_{eff\text{-}nr} \qquad k_{eff-nr} = k_{ET}(1 - QY_0) \qquad k_{rad} = \frac{1}{\tau_{rad}}$$

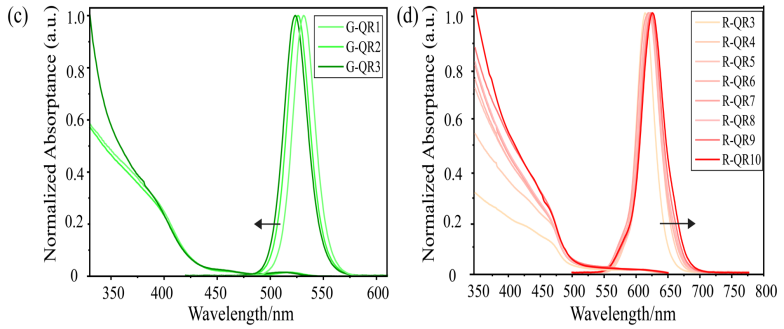
$$I = I_0 + A_1 e^{-\frac{t-t_0}{\tau_1}} + A_2 e^{-\frac{t-t_0}{\tau_2}} \qquad \tau_{avg} = \frac{A_1\tau_1^2 + A_2\tau_2^2}{A_1\tau_1 + A_2\tau_2}$$

Adv, Mat., 2104685, 2021
The Journal of Physical Chemistry A. 2013, 117(29), 5919-5925.
Adv Mater. 2014, 26(47), 8034-8040.
MRS Bull. 2013, 38(9), 721.

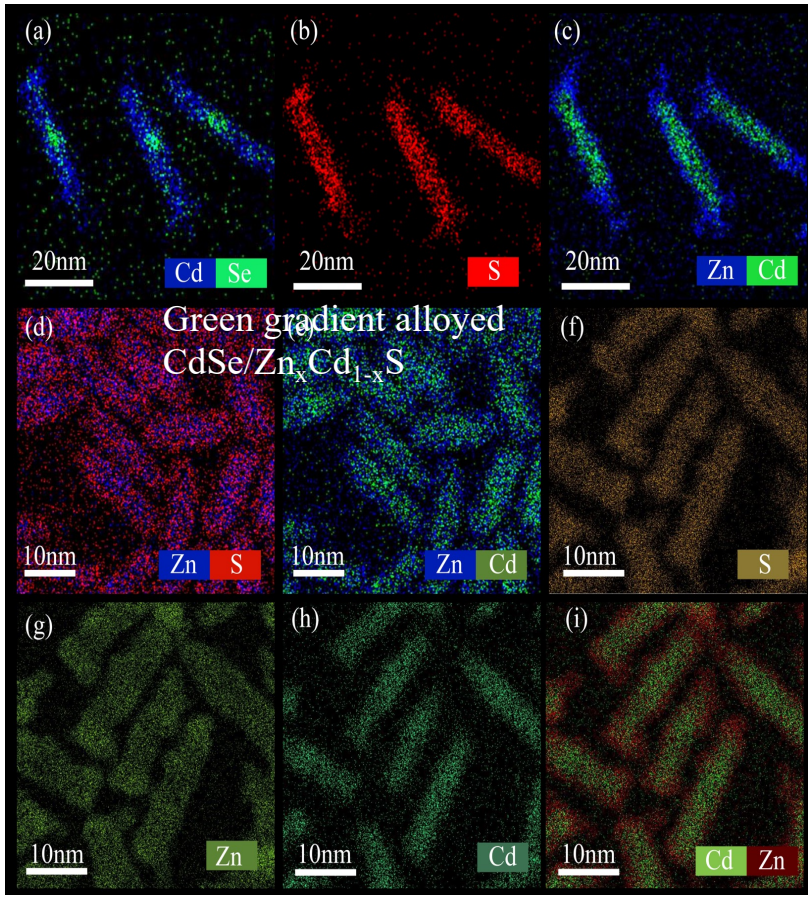
A thicker QR shell reduces the surface trap and increases the interparticle distance simultaneously and so increase the PLQY in the film.

Quantum Rods with additional shell



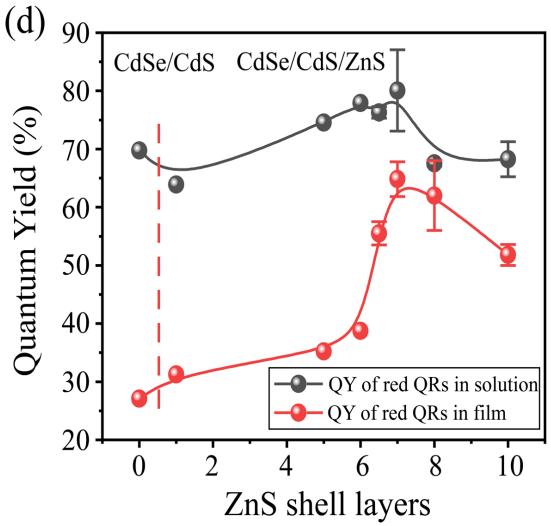


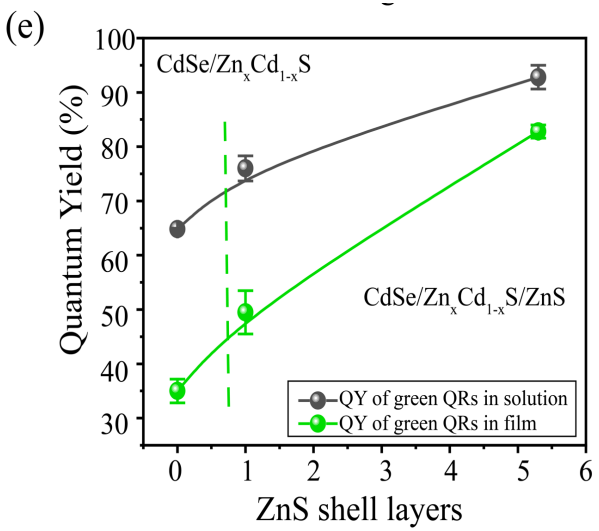
Red CdSe/CdS/ZnS QRs,

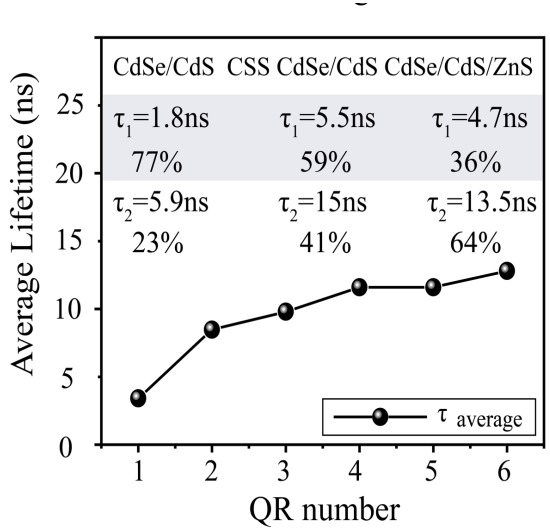


Adv, Mat., 2104685, 2021

Optical Properties of Quantum rods!





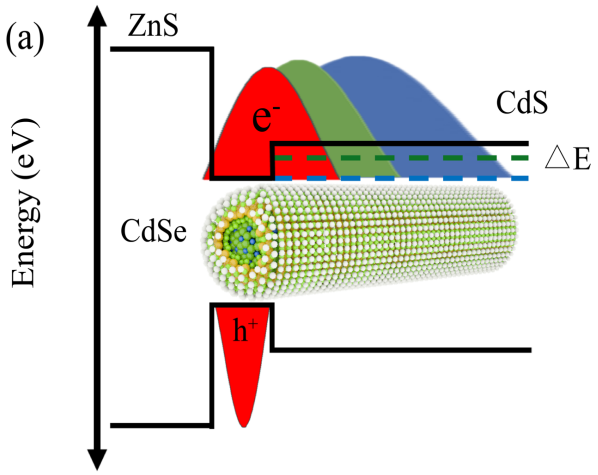


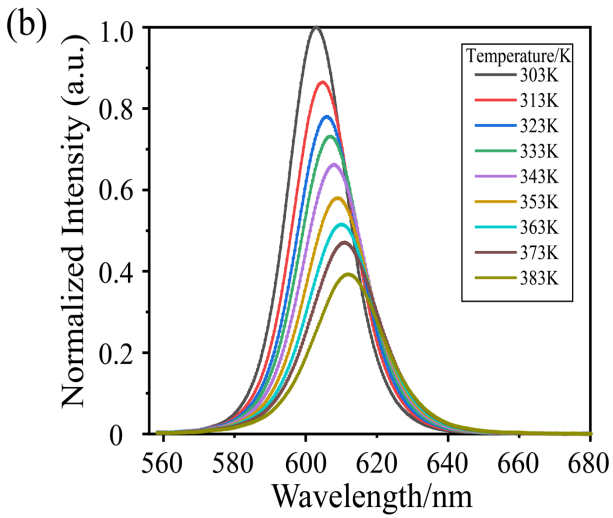
QR	Red QRs	Diameter(SD) /nm	Shell thickness(Avg)	Length(SD)/nm	Aspect ratio	Peak PL energy/eV
1	CdSe/CdS	3.2(0.40)	--	9.9(1.2)	3.1	2.05
2	CdSe/CdS	4.1(0.47)	--	20.1(1.4)	4.9	2.05
3	CdSe/CdS	4.6(0.61)	--	22.1(1.9)	4.8	2.01
4	CdSe/CdS/ZnS	4.7(0.97)	1st ZnS	24.2(2.3)	5.1	1.99
5	CdSe/ CdS/ZnS	5.9(0.57)	5th ZnS	26.1(2.3)	4.4	1.99
6	CdSe/ CdS/ZnS	6.2(0.73)	6th ZnS	28.0(2.5)	4.5	1.99
7	CdSe/ CdS/ZnS	6.3(0.74)	6.5th ZnS	29.5(2.8)	4.6	1.99
8	CdSe/ CdS/ZnS//ZnS	6.5(0.88)	7th ZnS	31.0(3.6)	4.7	1.99
9	CdSe/ CdS/ZnS//ZnS	7.0(1.04)	8th ZnS	30.8(3.4)	4.4	1.99
10	CdSe/ CdS/ZnS//ZnS	8.1(1.24)	10th ZnS	36.9(4.1)	4.5	1.98

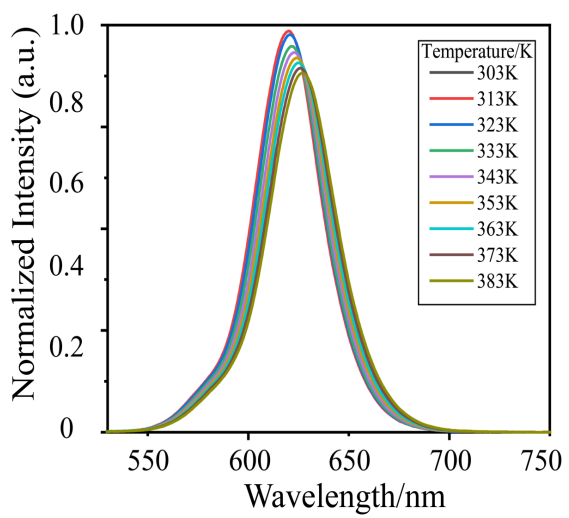
The PLQY of QR in thin films improved!

Adv, Mat., 2104685, 2021

Optical Properties of Quantum Rods!







Varshni Equation

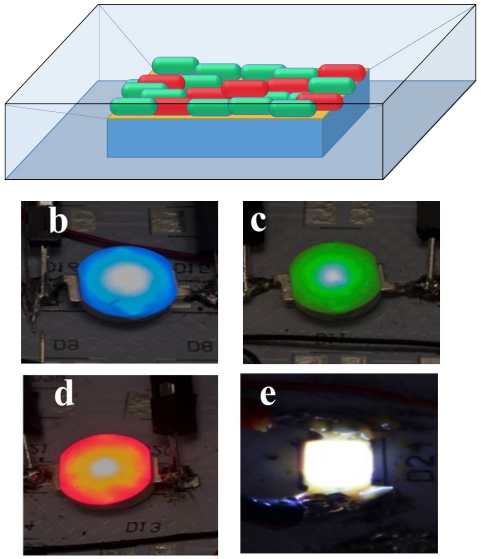
$$E_g(T) = E_g\,(0) - \frac{\alpha T^2}{(\beta + T)}$$

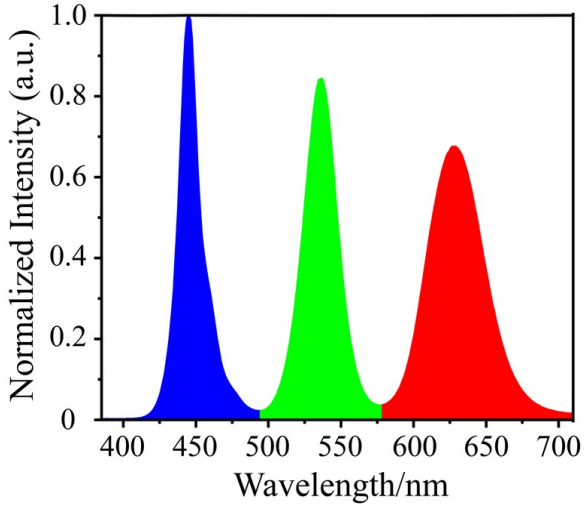
Here, E (0) is the energy gap at 0 K, α represents the temperature coefficient while β represents Debye temperature.

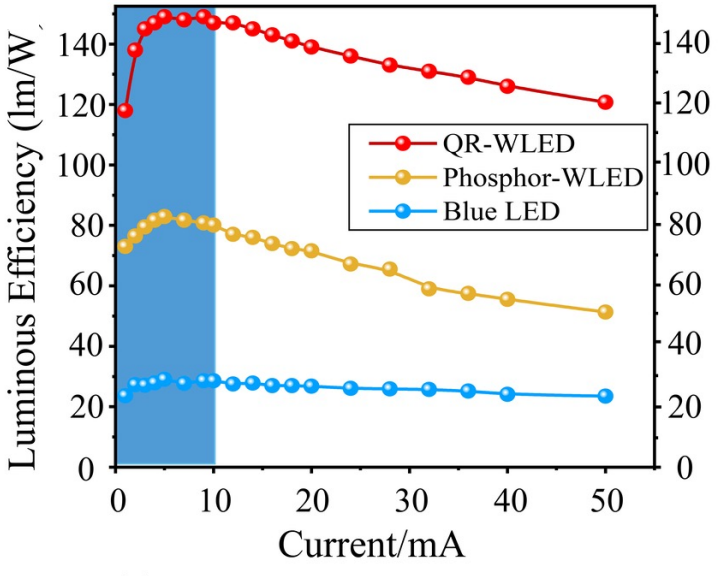
	CdSe/CdS	CdSe/$Zn_xCd_{1-x}S$/ZnS
α	$3.9\times10^{-4} eV/K$	$5.15\times10^{-4} eV/K$
β	178K	196K

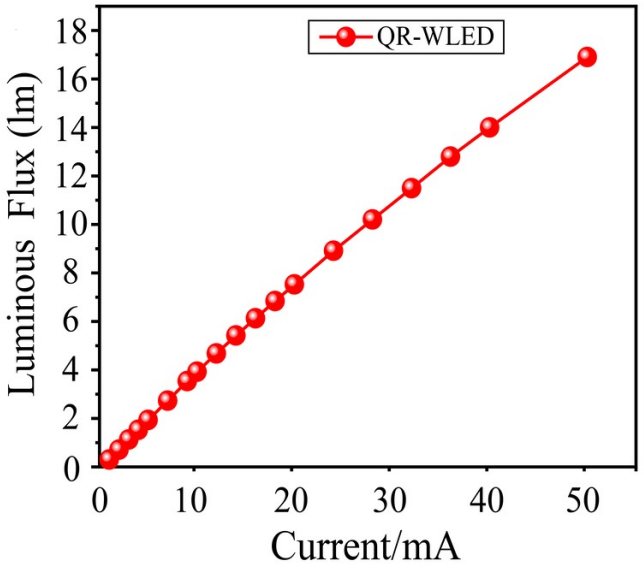
Adv, Mat., 2104685, 2021

QR-based Display LEDs



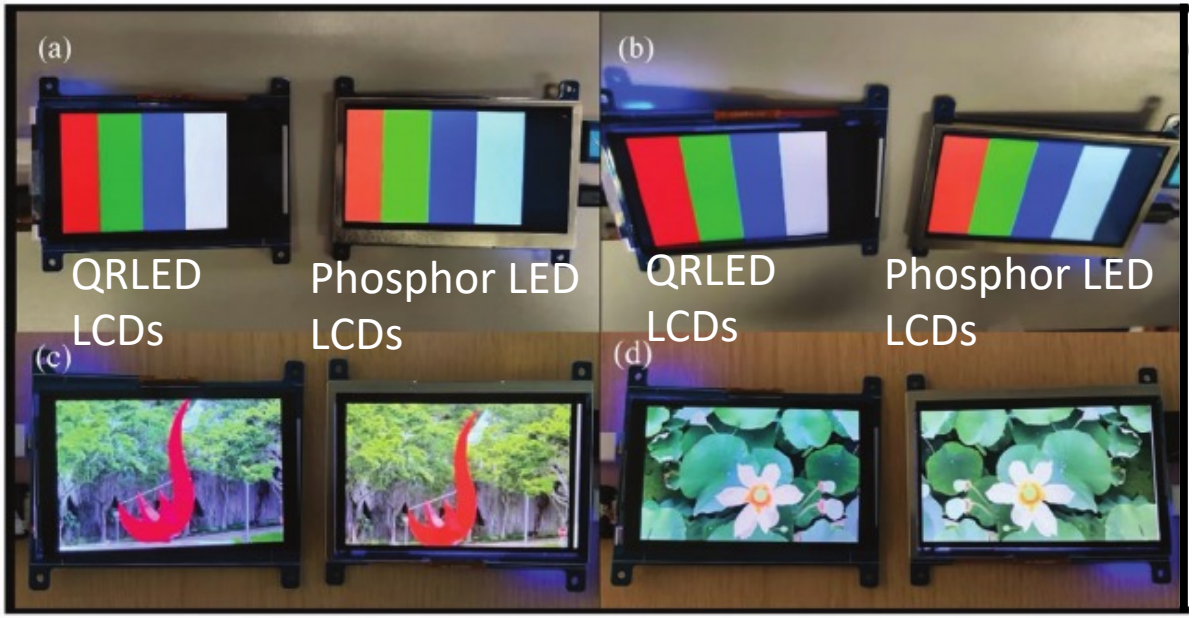


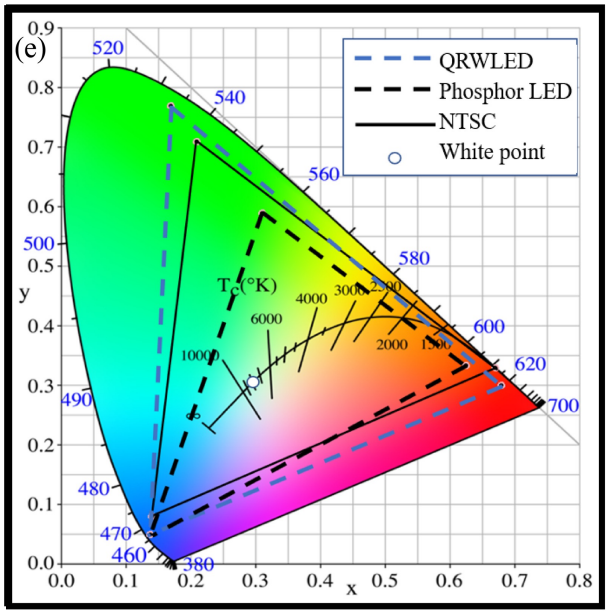




Adv. Mat., 2104685, 2021

QRLEDs makes the display better in the same cost

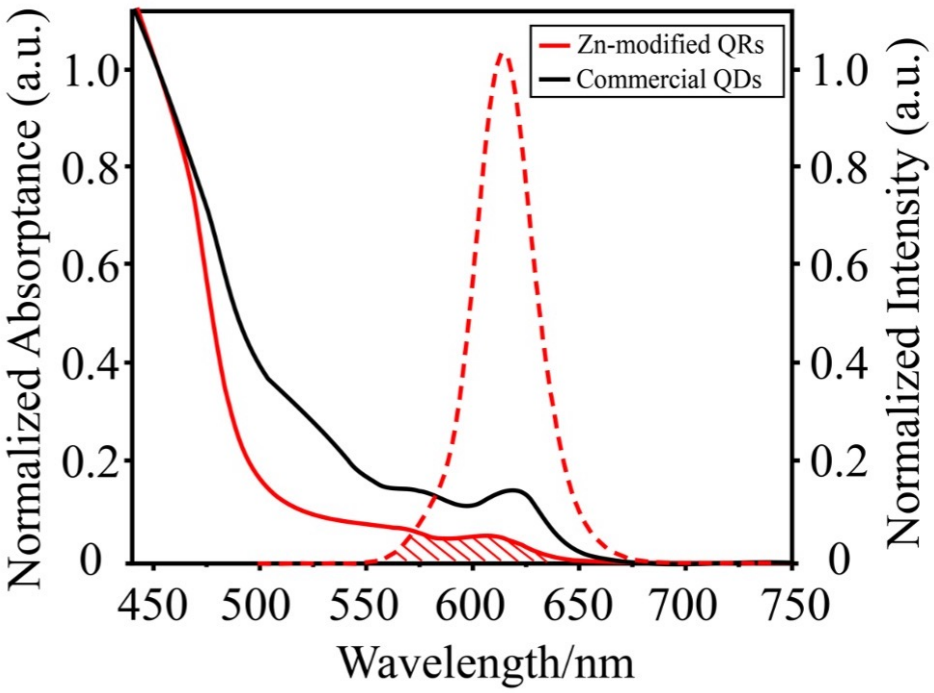


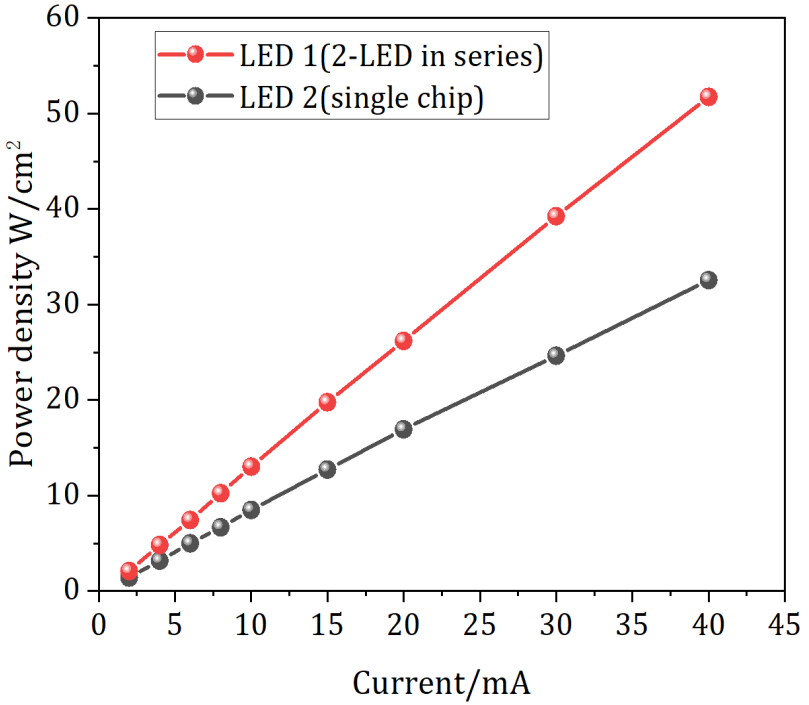


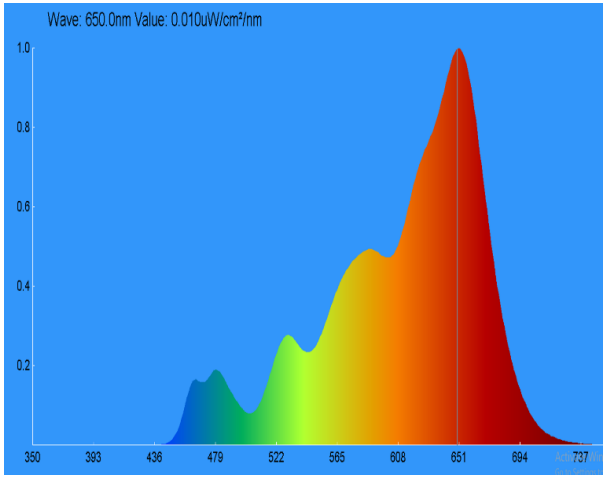
QRLED covers more than 118% NTSC color gamut.

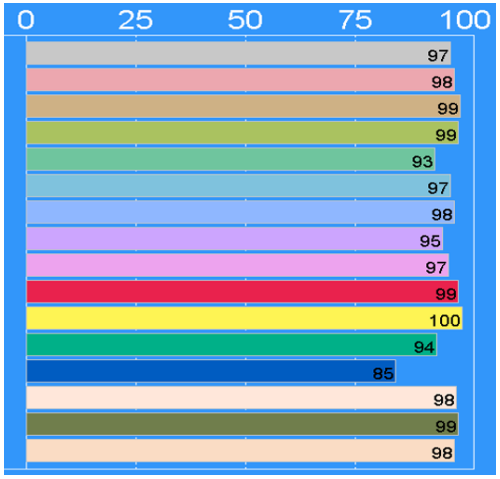
Adv. Mat., 2104685, 2021

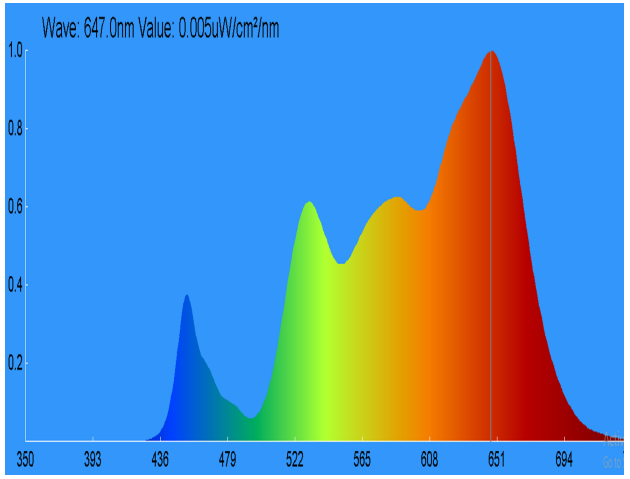
Blue Light Hazard Concern: QRLEDs can help





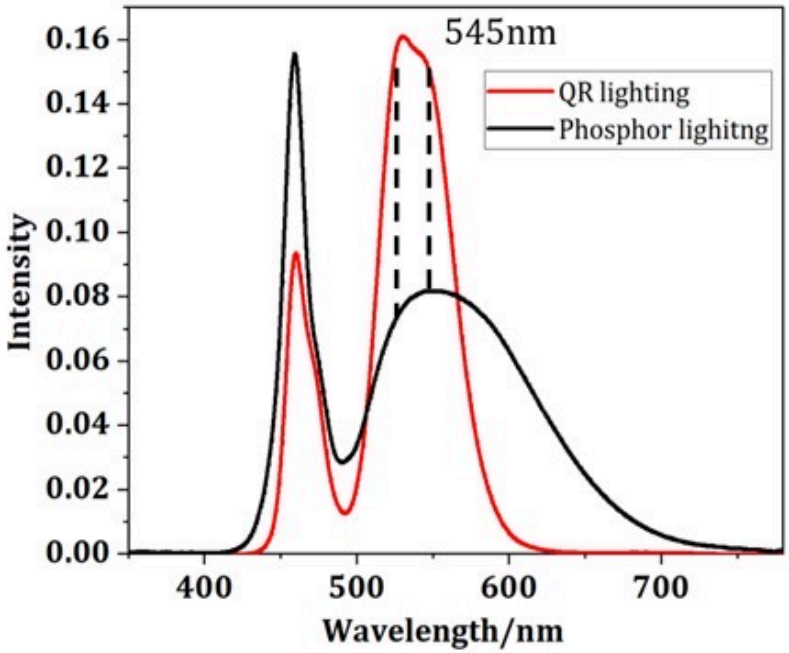


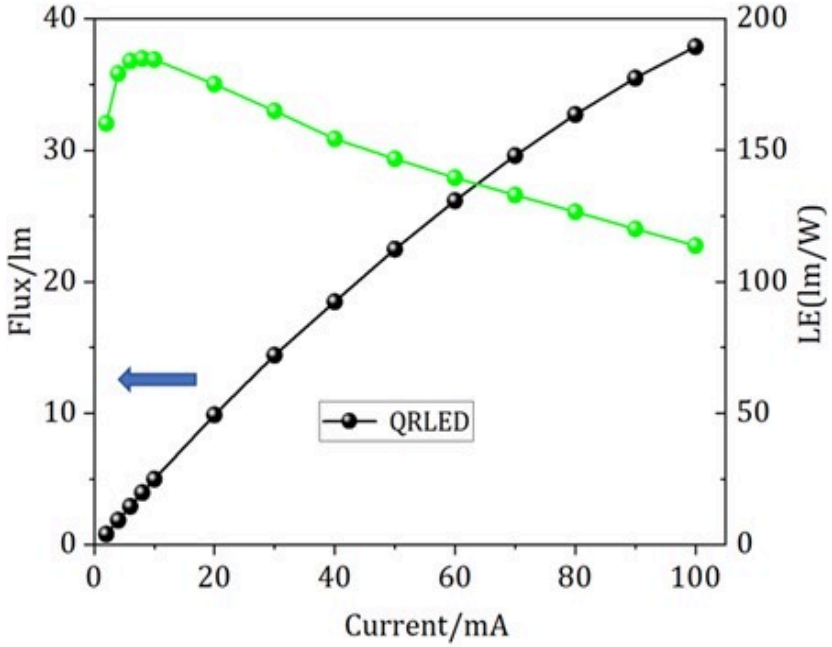




Submitted, 2022.

On-Chip LEDs for Lighting





Submitted, 2022.

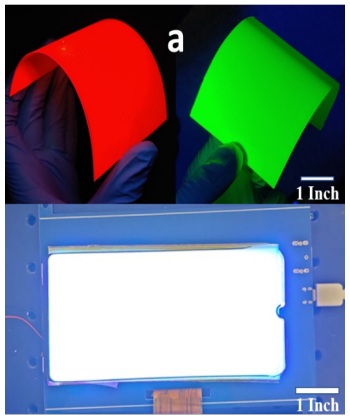
Quantum rods offer better efficiency and saturated color

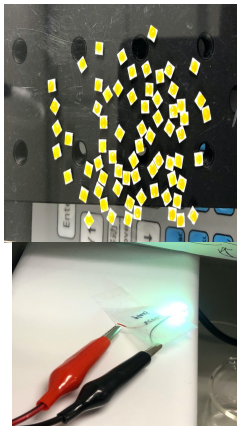
Emitting Material	Methodology	CCT (K)	Color gamut(%)	LE (lm/W)	Year	Ref
CdSe//ZnS/CdSZnS	Liquid type QD	-	-	103	2018	Optica. 2018, 5, 793
CsPbBr3CsPbBr1.2I1.8	Liquid type perovskite	5516	122	51	2019	Phot. Res. 7, 579.
RbNa(Li3SiO4)2: Eu2+	Narrow bandwidth phosphor	5196	113	111	2019	Adv. Func. Mat. 1901988.
Cs3Mn0.96Zn0.04Br5 K2SiF6:Mn4+	Narrow bandwidth phosphor	6723	101	108	2019	*J. of Mat. Chem. C.* **2019**, 7, 11220
CdSe/ZnxCd1-xS	Gradient alloyed QRs	8909	122	115	2021	Small, 17, 2004487.
QD/SBA-15	Matrix reduces reabsorption	6500	118	136.7	2021	ACS Nano, 15, 550-562
CdSe/CdS/ZnS/ZnS CdSe/ZnxCd1-xS/ZnS	High solid-state QY QRs with less reabsorption	6500	118	149	2021	***Adv, Mat., 2104685, 2021***

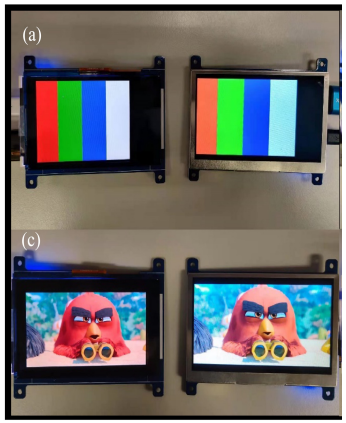
- Quantum rods offer better opportunity for downconverter material.
- Lifetime is still an issue (we have already achieved T_{90} of 400 h).

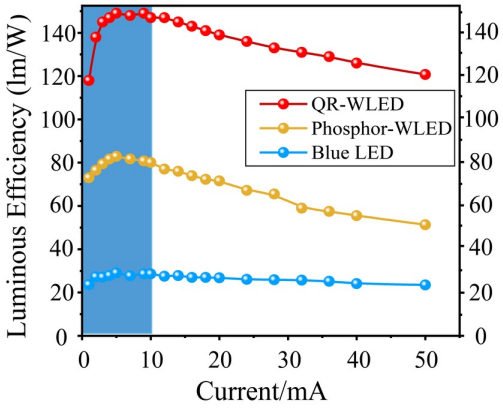
Take Away Message-1!

- Low Cd QRs meet the limitation from RoHS.
- Blue QRs improves the performance QREF.
- QRLED offer 149lm/W and 90% of BT2020 in 1931 color space!
- QRLED can achieve high efficacy ~200 lm/w and CRI >95.









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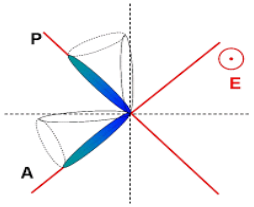
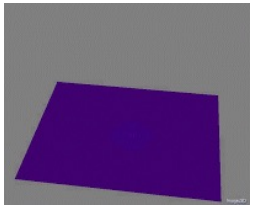
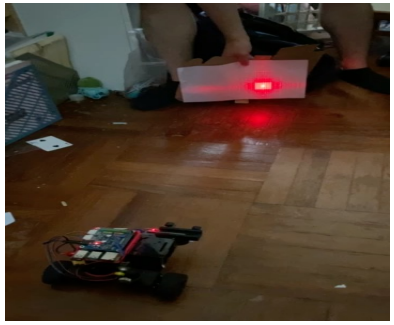
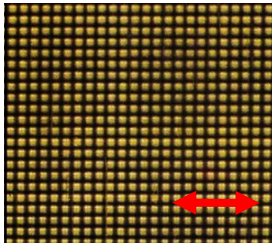
QREF **QR LEDs** **QRLEDs- LCD Backlight**

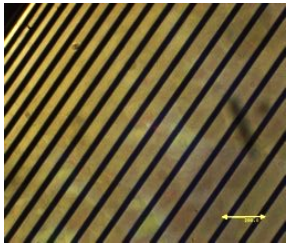
- DHFLC show No/extremely small Fringing field effect.
- Good for high resolution Display and Photonics.
- DHFLC based WSS are fast and efficient.
- FLC polarization dependent lenses are fast can be used for AR/VR.
- LiDAR based on FLC Dammann grating offer many advantages over commercial Lidar

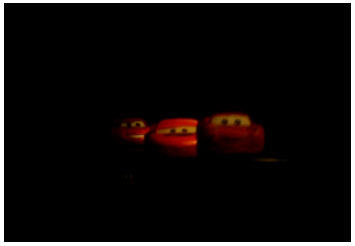












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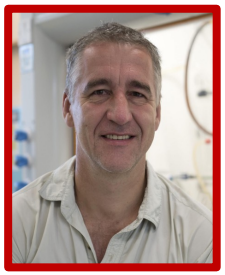
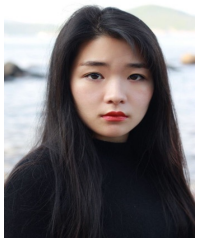
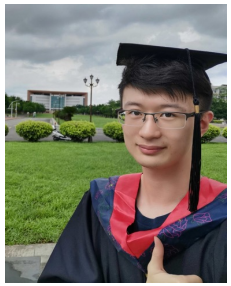
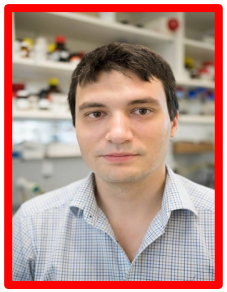
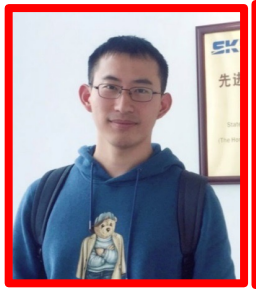
FLCD 3μm pixel pitch **FLC based WSS** **FLC PD Lens** **FLC LiDAR**

Acknowledgements!

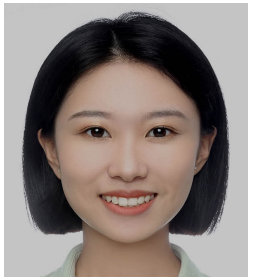






Grants

HK GOV. ITC Grant: - PRP/049/19FX
HK Gov. ITC Grant: -ITS/370/16
HK Gov. RGC.26202019
Microlite Corp. ltd.
Huawei Technologies Co., Ltd.
Trans consultant ltd.
Sanma electronic ltd.
AUO, Taiwan
Solid lighting ltd.
State Key Lab ADO, Hong Kong.

Collaborators

Prof. Jonathan Halpert (HKUST)
Prof. Andrey Rogach (CITYU, HK)
Prof. Ian Underwood (Edinburgh U. UK)
Prof. K. S. Wong (HKUST)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