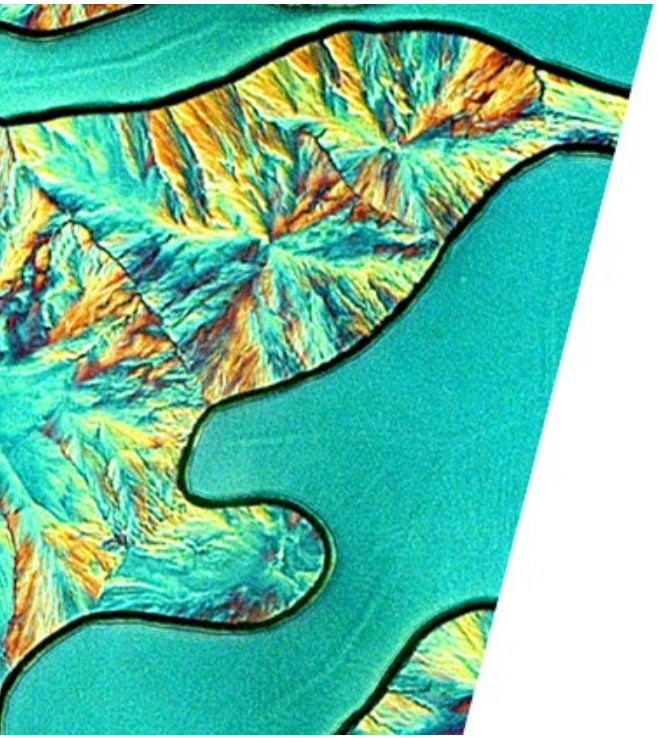
The OSA Nonlinear Optics Technical Group Welcomes You!



High-Order Dispersion Solitons and Topological Photonics in Silicon

Andrea Blanco-Redondo

OSA Nonlinear Optics Technical Group

Technical Group Leadership 2021

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Communications Officer
Lin Xu
Univ. of Southampton, UK

Webinar Officer
Alexander Solntsev
University of Technology Sydney, AU

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OSA Nonlinear Optics Technical Group

Technical Group at a glance

- Focus
  - "Physics of nonlinear optical materials, processes, devices, & applications"
  - **3800** members (**largest** in OIS, 3rd largest in OSA)
- Mission
  - To benefit *YOU*
  - webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at
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  - LinkedIn: www.linkedin.com/groups/8302249

Today's webinar

High-Order Dispersion Solitons and Topological Photonics in Silicon

Short bio:

- 2019 – now: Head of the Silicon Photonics department at Nokia Bell Labs
- 2015 – 2019: Professor Harry Messel Research Fellow and Senior Lecturer at the School of Physics of the University of Sydney, Australia
- 2007 – 2015: photonics researcher and a project manager with the Aerospace and Telecom departments of Tecnalia, Spain
- 2014: PhD in photonics at the University of the Basque Country, Bilbao, Spain
- OSA Director at Large, Member of the OSA Finance Council, Associate Editor at OSA Continuum

NOKIA Bell Labs

High-order dispersion solitons and topological photonics in silicon

Andrea Blanco-Redondo

Nokia Bell Labs, New Providence, NJ, USA

andrea.blanco-redondo@nokia-bell-labs.com

Collaborators

Bell Labs (NJ, US):
Rene Essiambre, Nick Fontaine, Mark Earnshaw, Brian Stern, KW Kim, Mikael Mazur …

University of Sydney (Sydney, Australia):
Martijn de Sterke, Antoine Runge, Bryn Bell, Wei-Wei Zhang, Steven Bartlett, Ben Eggleton, Chad Husko, Alessio Stefani

Students: Michelle Wang, Cooper Doyle, Sam Lo, Kevin Tam, Joshua Lourdesamy, Imanol Andonegui, Ezgi Sahin

Macquarie University (Sydney, Australia):

Darren Hudson (now CACI), Matthew Collins (now Xanadu)

Technion (Haifa, Israel):
Moti Segev, Dikla Oren, Gal Harari, Kobi Lumer, Mik Rechtsman (now Penn State)

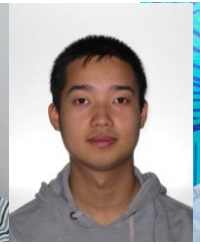
University of York (York, UK):
Thomas Krauss, Juntao Li

Soliton work

Prof. M. de Sterke
Usyd

Dr. Antoine Runge
Usyd

Dr. Darren Hudson
CACI – Photonics solutions

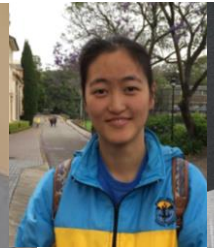


Mr. Kevin Tam
Usyd

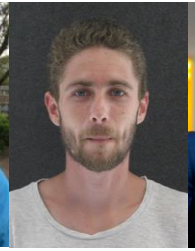
Dr. Chad Husko
Argonne Nat. Lab

Topological quantum work

Dr. Bryn Bell
Imperial College



Ms. Michelle Wang
Usyd



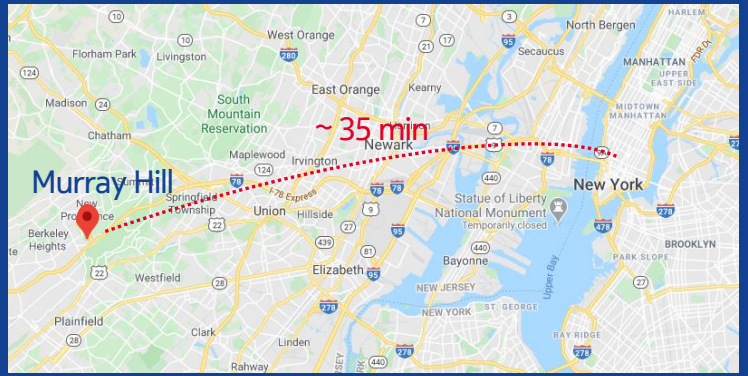
Mr. Cooper Doyle
Usyd

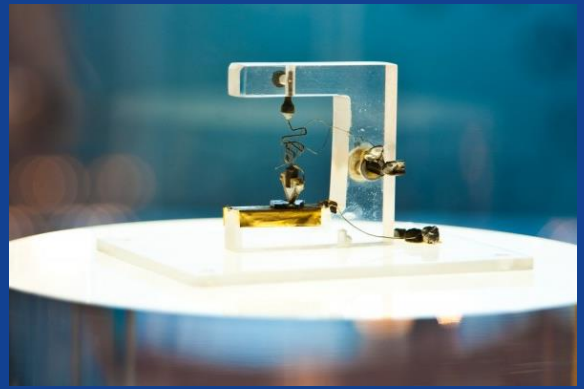
Prof. Ben Eggleton
Usyd

Prof. Moti Segev
Technion

Bell Labs

Murray Hill, New Providence, NJ – BELL LABS HEADQUARTERS





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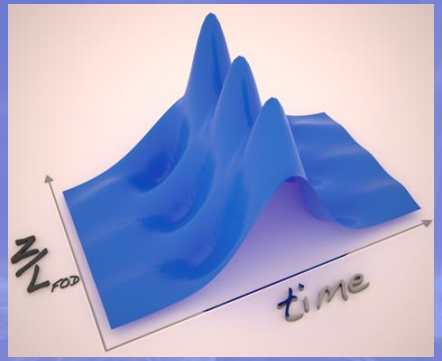
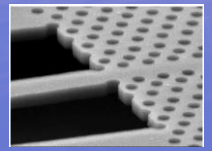
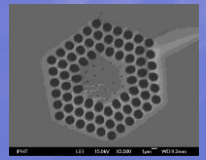
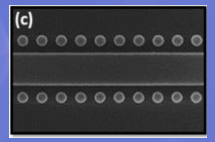
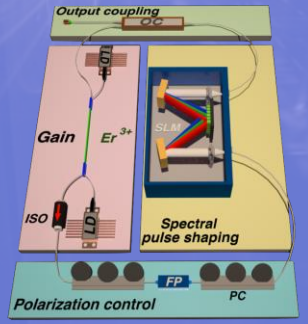
PART 1:
NOVEL SOLITON PHYSICS AND TECHNOLOGIES











Runge at al. *Phys. Rev. Res*. 3, 013166 (2021)
Runge et al. *Nat. Photonics* 14, 492-497 (2020).
Sahin, Blanco-Redondo, et al. *Laser & Photonics Reviews* 13, (2019)
Blanco-Redondo et al. *Nature Comm*. **7,** 10427 (2016)
Blanco-Redondo et al. *Nature Comm*. **5,** 3160 (2014)
Blanco-Redondo et al. *Optica* **1,** 299-306 (2014)

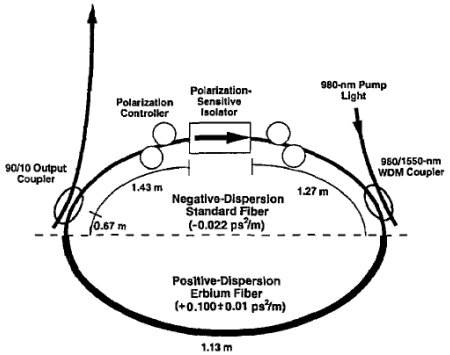
PART 2:
TOPOLOGICAL QUANTUM PHOTONICS

Doyle et al. (in preparation)
Khan et al. *Advanced Materials Technologies*, 2100252 (2021)
Blanco-Redondo, *Proceedings of the IEEE* **108,** 837-849 (2020)
Wang et al. *Nanophotonics* **8**, 1327–1335 (2019)
Blanco-Redondo et al. *Science* **362,** 568-571 (2018)
Blanco-Redondo et al. *Phys. Rev. Lett.* **116,** 163901 (2016)

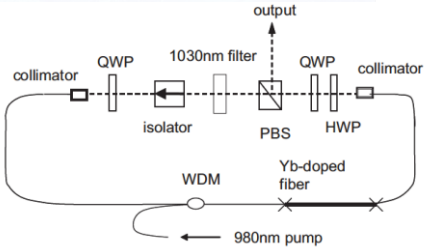
Solitons: the interplay of negative dispersion and positive nonlinearity

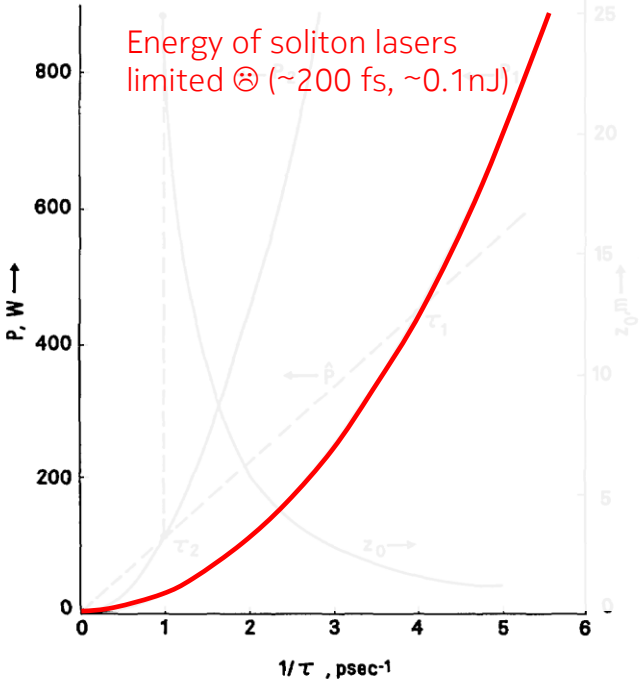
Other cavity configurations :

Stretched-pulse laser invented @MIT
Tamura, Ippen, Haus & Nelson, Opt. Lett. (1993)

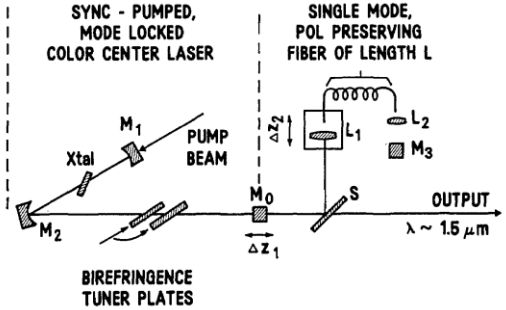


ANDi laser invented @Cornell
Chong, Buckley, Reninger & Wise, Opt. Exp. (2006)





The soliton laser invented @Bell Labs
Mollenauer & Stolen Opt. Lett. (1984)



*"..., the soliton laser would most probably take the form of a **single loop of fiber closed upon itself.** The **simplicity and low cost** of such devices would make them most attractive."*

Fixed Energy-width relation:
a blessing and a curse

$$E_S \propto \frac{1}{\tau}$$

Well-defined shape (sech²)

Transformed limited pulses (unchirped)

Bell Labs

Soliton functionality in silicon

A complicated affair

Negative β_2 required

Nonlinear Schrödinger Eq.

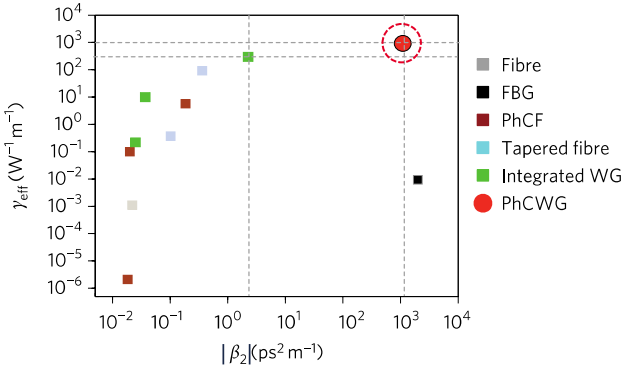
$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + i\gamma|A|^2 A$$

vs.

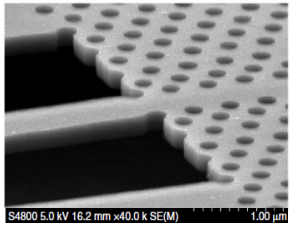
Negative β_2 required

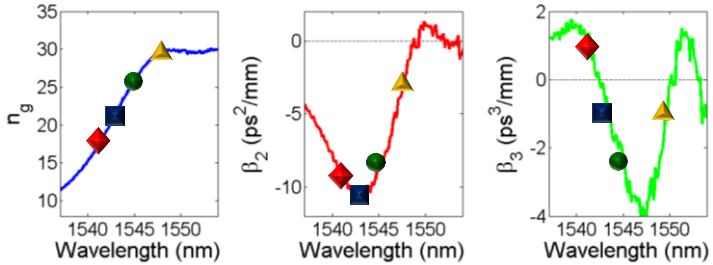
Generalized Nonlinear Schrödinger Eq. in Silicon

$$\frac{\partial A}{\partial z} = -\frac{\alpha_l}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} + \left(i\gamma - \frac{\gamma_{TPA}}{2}\right)|A|^2 A + \left(ik_0 n_{FC} - \frac{\sigma}{2}\right)N_c A$$



Colman*, Husko*, Combrie* et al, *Nature Photonics* **4**, 862 (2010)





▲ **Solitons**: moderate anomalous dispersion, high n_g (nonlinearity), low third order dispersion

Blanco-Redondo et al, *Nature Commun.* **5**, 3160 (2014)

◆ ■ ● **Free-carriers dominate nonlinear pulse propagation**:

- Anomalous dispersion + Free-carrier dispersion → Nonlinear temporal broadening (x2)
- Third order dispersion can counteract this and other nonlinear free-carrier effects

Blanco-Redondo et al, *Optica* **1(5)**, 299 – 306 (2014)

Pure-quartic solitons in silicon

A novel kind of pulse

Negative β_2 required

Biharmonic Nonlinear Schrödinger Eq.

$$\frac{\partial A}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + i\frac{\beta_4}{24}\frac{\partial^4 A}{\partial T^4} + i\gamma|A|^2 A$$

Negative β_4 required

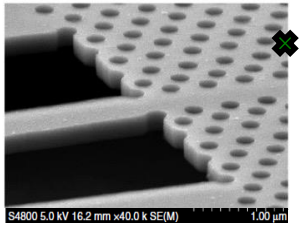
vs.

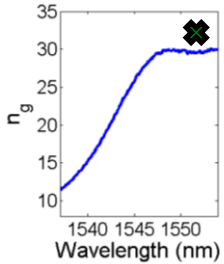
Negative β_2 required

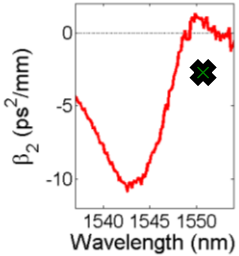
Generalized nonlinear Schrödinger Eq. in Silicon

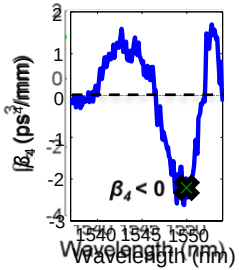
$$\frac{\partial A}{\partial z} = -\frac{\alpha_l}{2}A - \frac{\alpha_l}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \frac{\partial^2 \beta_2}{\partial T^2}\frac{\partial^2 A}{\partial T^2} + \frac{\partial^3 \beta_3}{\partial T^3}\frac{\partial^3 A}{\partial T^3} + i\frac{\beta_4}{24}\frac{\partial^4 A}{\partial T^4} + \left(i\gamma + \frac{\gamma_{TPA}}{2}\right)|A|^2 A + \frac{\gamma_{FPA}}{2}A + \left(ik_0 n_2 - \frac{\sigma}{2}\right)N_c A$$

Negative β_4 required









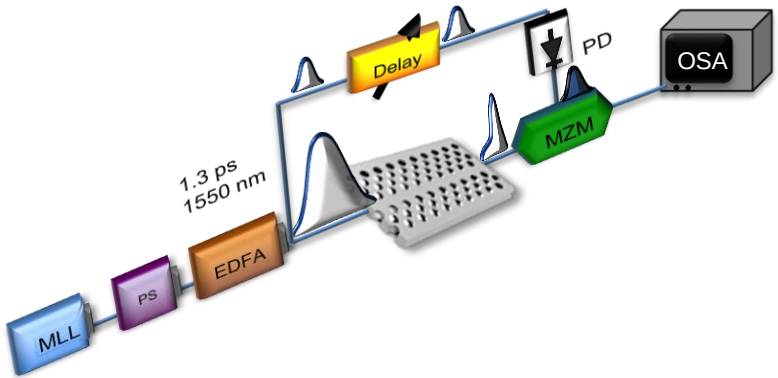
✖ Dominant (negative) quartic dispersion balanced by nonlinearity: **Pure-quartic solitons**

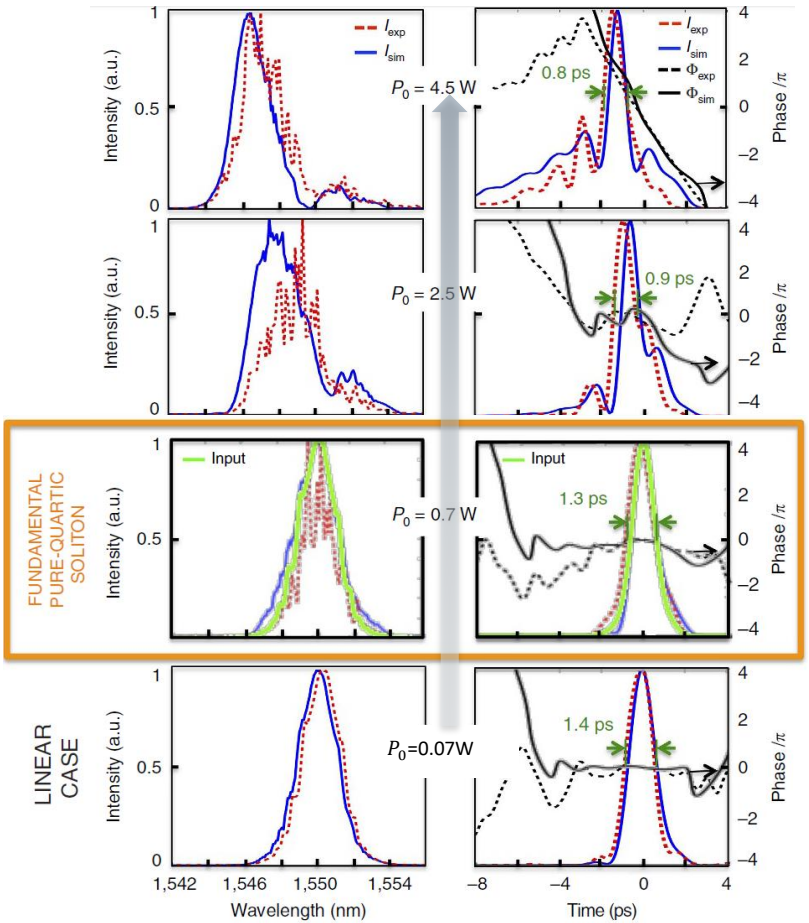
Blanco-Redondo et al, *Nature Commun.* **7**, 10427 (2016)

Pure-quartic solitons in silicon

A novel kind of pulse

Frequency resolved electrical gating
Dorrer and Kang, Opt. Lett 27(15), 1315-1317 (2002)





Soliton compression

Soliton shape-preservation

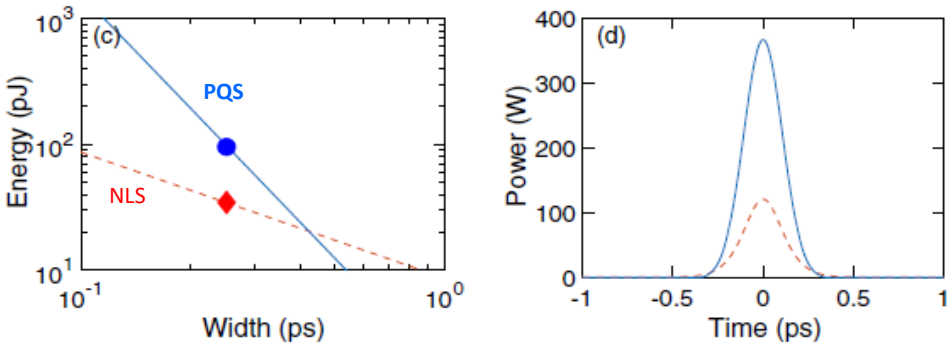
Dispersive temporal broadening

Blanco-Redondo et al, *Nature Commun.* **7**, 10427 (2016)

Bell Labs

Pure-quartic solitons

What is useful about them?



K.K.K. Tam, T. Alexander, A. Blanco-Redondo and C. Martijn de Sterke *Opt. Lett.* **44**, 3306 (2019).

- Shape differs from *conventional* NLS soliton.
- Time-bandwidth product:

$$TBP_{PQS} = 0.53 \text{ vs } TBP_{NLS} = 0.315$$

- Different energy-width scaling relations!

$$E_{\mathrm{PQS}} = \frac{2.87|\beta_4|}{\gamma\tau^3}$$

$$E_{PQS} \propto \frac{1}{\tau^3} \text{ vs } E_{NLS} \propto \frac{1}{\tau}$$

A PQS laser could emit transform-limited pulses with higher energies than conventional NLS soliton lasers at short durations

The pure-quartic soliton laser

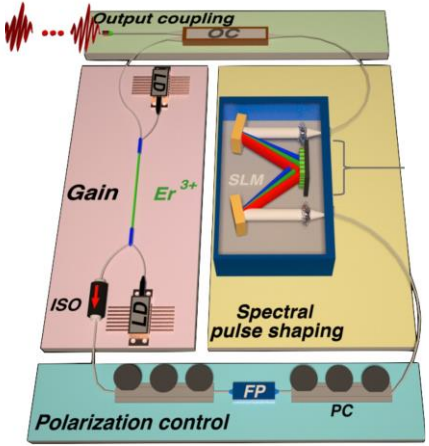
Overcoming energy limitations in soliton lasers

Need a laser cavity with **dominant negative quartic dispersion**

- How about photonic crystal fibers? Yes, but challenging

Lo, Stefani, Martijn de Sterke, and Blanco-Redondo *Opt. Exp.* ***26(6)***, 7786-7796 (2018)

- How about a dispersion-managed approach using a pulse-shaper?



- Soliton laser using NPE for mode-locking.
- **Intracavity pulse-shaper** allows for the tuning of the **net cavity dispersion**.

J. Schröder, *et al. Opt. Express.* **18**, 22715 (2010).

J. Peng and S. Boscolo *Sci. Rep.* **6**, 25995 (2016).

A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, "The pure-quartic soliton laser," *Nature Photonics* 14, 492-497 (2020)

The pure-quartic soliton laser

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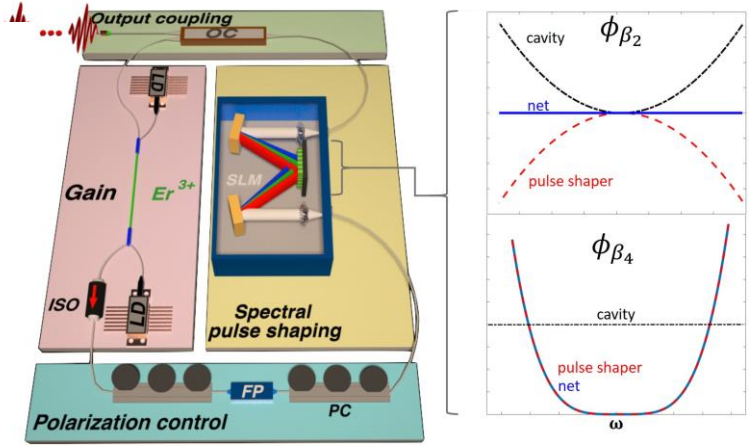


- Pulse-shaper applies a **phase mask** to compensate for β_2 and β_3 of the fibres, and induces a **large negative quartic** (β_4) dispersion.
- Cavity length L = 21.4 m, opposite 2nd and 3rd order dispersion of SMF $\boldsymbol{\beta_2}$ **= +21.4 ps²/km**, $\boldsymbol{\beta_3}$ **=-0.2 ps³/km.**
- $\boldsymbol{\beta_4}$ **=-80 ps⁴/km** is chosen to be much larger than intrinsic 4th order dispersion of SMF

A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, "The pure-quartic soliton laser," *Nature Photonics* 14, 492-497 (2020)

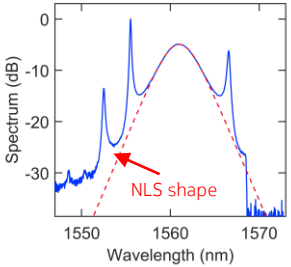
The pure-quartic soliton laser

Overcoming energy limitations in soliton lasers

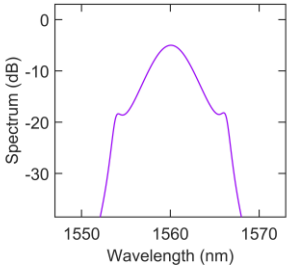
Measurements by
Dr. Antoine Runge

NLS Soliton laser

MEASUREMENTS



LASER SIMULATIONS

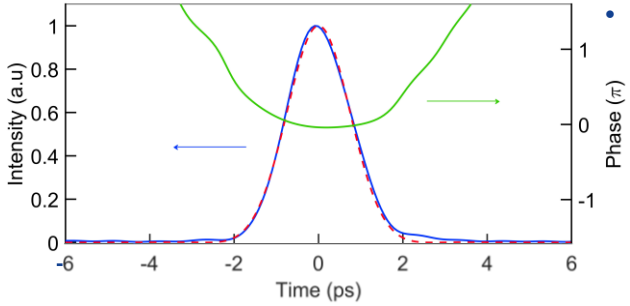


- Phase mask **OFF**, laser operates in conventional soliton regime.
- Phase mask **ON**, different output pulse spectrum (blue). Good fit with calculated PQS shape (dashed red).

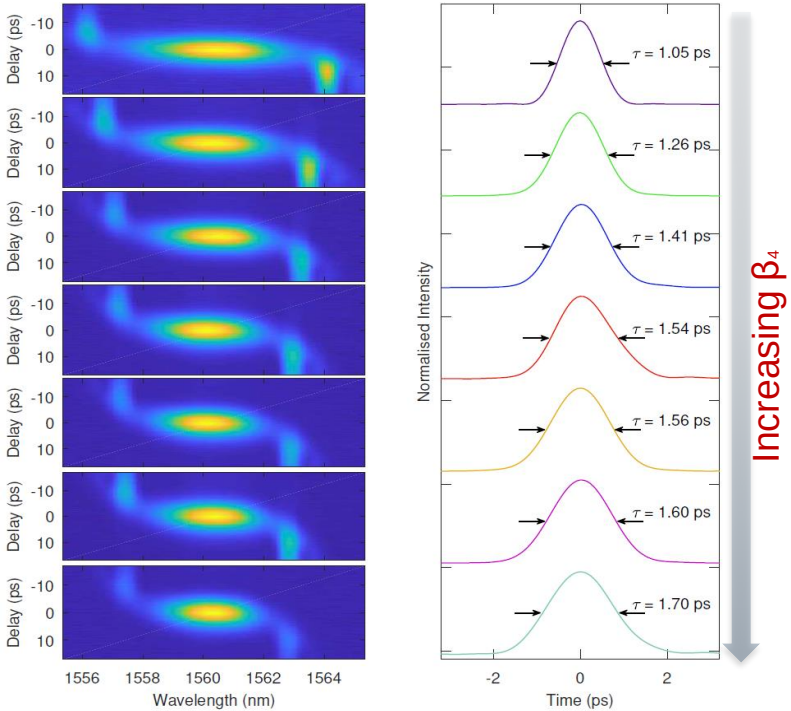
A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, “The pure-quartic soliton laser,” *Nature Photonics* 14, 492-497 (2020)

The pure-quartic soliton laser

Overcoming energy limitations in soliton lasers



- Nearly-flat phase → Nearly transform limited



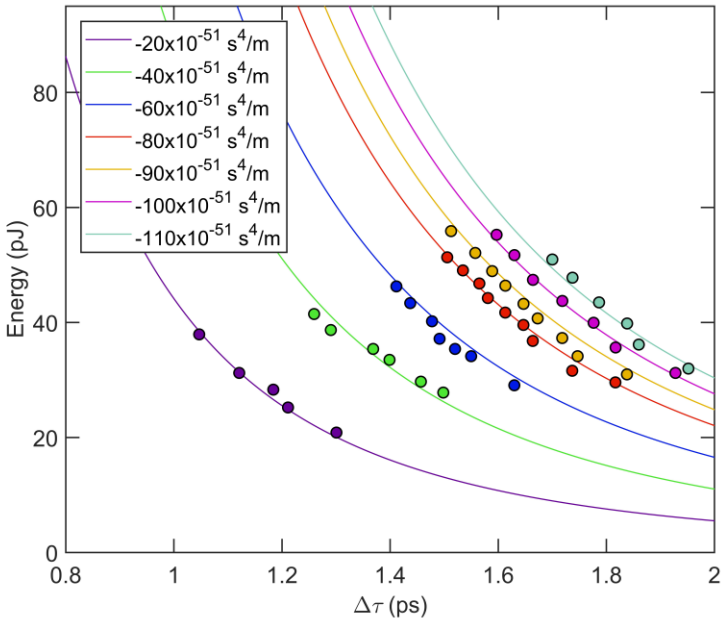
- Adjustable spectrum and temporal profile by changing the dispersion provided to the pulse shaper

A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, "The pure-quartic soliton laser," *Nature Photonics* 14, 492-497 (2020)

Bell Labs

The pure-quartic soliton laser

Overcoming energy limitations in soliton lasers



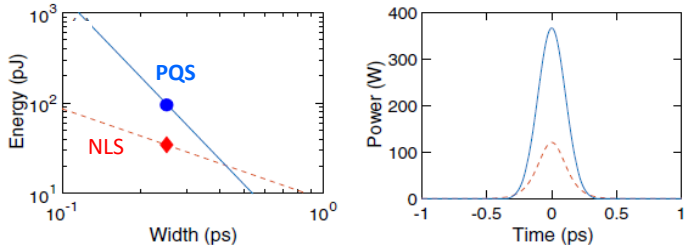
Energy-width scaling relation

- We have demonstrated that the energy scales as predicted:

$$E_{\mathrm{PQS}} = \frac{2.87|\beta_4|}{\gamma\tau^3}$$

- First step towards solving soliton laser limitations:

$E_{PQS} \propto \frac{1}{\tau^3}$ vs $E_{NLS} \propto \frac{1}{\tau}$



*"The **simplicity and low cost** of such devices would make them most attractive."*
Mollenauer and Stolen, Opt. Lett. (1984)

A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, "The pure-quartic soliton laser," *Nature Photonics* 14, 492-497 (2020)

The pure-quartic soliton laser

Overcoming energy limitations in soliton lasers

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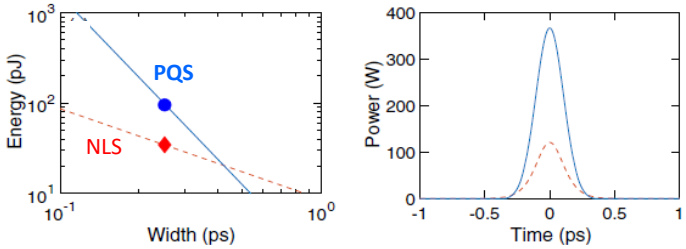

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A. J. Runge, D. D. Hudson, K. K. K. Tam, C. Martijn de Sterke, and A. Blanco-Redondo, "The pure-quartic soliton laser," *Nature Photonics* (2020) https://doi.org/10.1038/s41566-020-0629-6

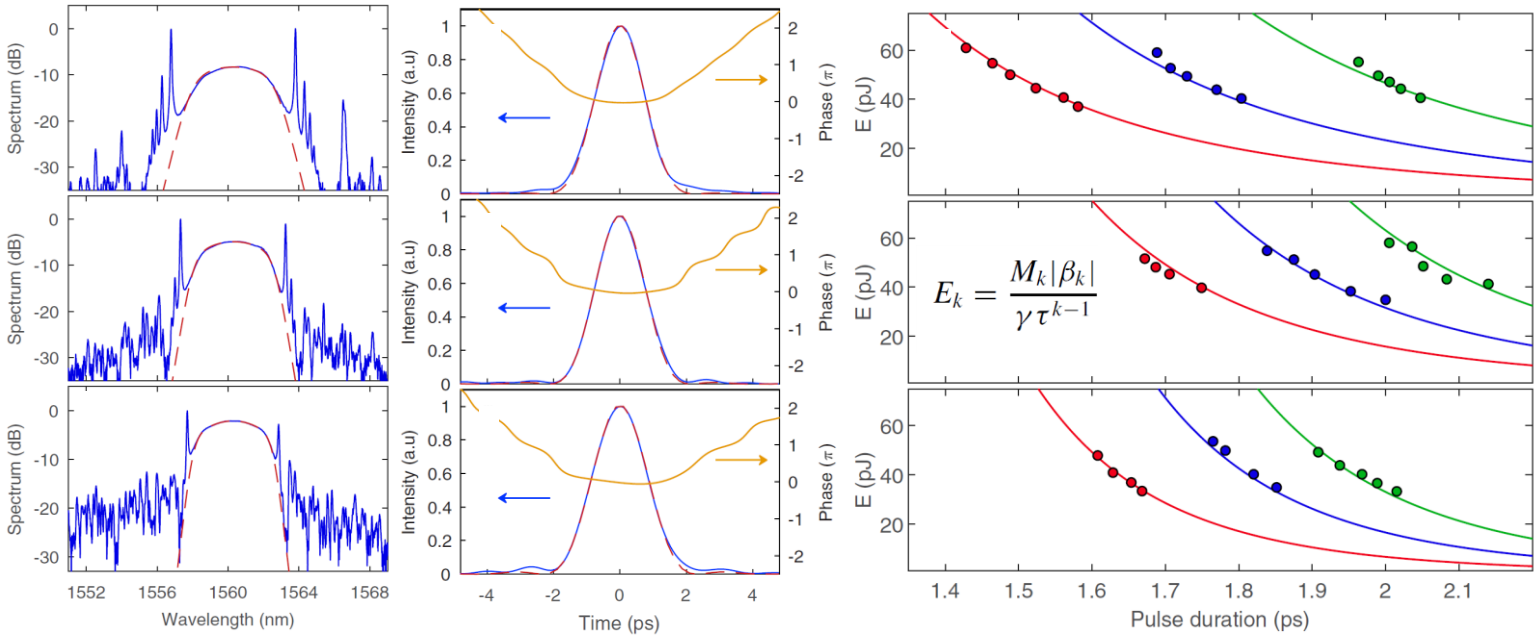
How about other even orders of dispersion?

Pure-sextic, pure-octic, pure-decic soliton lasers?

Pure-sextic soliton
β_6

Pure-octic soliton
β_8

Pure-decic soliton
β_{10}



Runge, Hudson, Martijn de Sterke and Blanco-Redondo CLEO 2020 (paper JTh4B.1) - Postdeadline Paper
Runge, Qiang, Alexander, Rafat, Hudson, Blanco-Redondo and Martijn-de Sterke, Phys. Rev. Res. 3, 013166 (2021)

End of Part 1

Conclusions

Solitons and other nonlinear effects in silicon are challenging but possible

Demonstrated new type of mode-locked laser emitting pure-quartic, pure-sixtic, pure-octic… solitons

- Energy-width scaling

The desired higher-order dispersion profile can be achieved via:

- Dispersion engineering
- Pulse shaping element

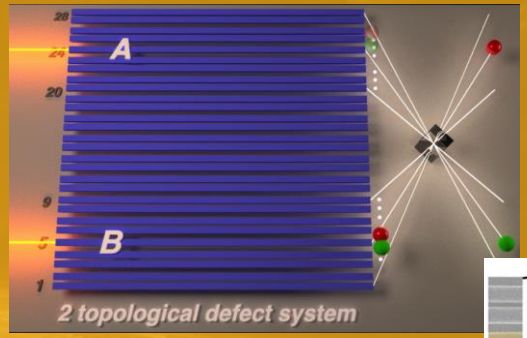
Higher-order dispersion can be more than the ugly duckling

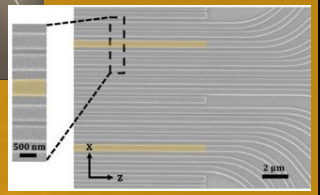
Bell Labs

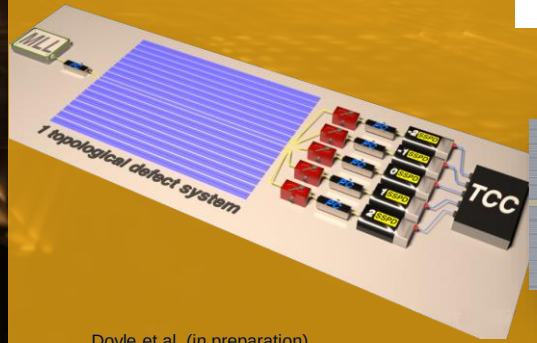
PART 1:
NOVEL SOLITON PHYSICS AND TECHNOLOGIES

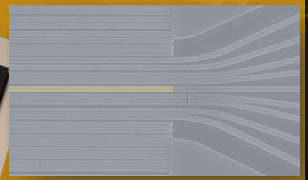
Runge et al. Nature Photonics *Nat. Photonics* (2020). https://doi.org/10.1038/s41566-020-0629-6
Tam et al. *Physical Review A* **101**, 043822 (2020)
Tam et al. *Opt. Lett.* **44**, 3306 (2019)
Sahin et al. Laser & Photonics Reviews 13(8) (2019)
Blanco-Redondo et al. *Nature Comm.* **7**, 10427 (2016)
Blanco-Redondo et al. *Nature Comm.* **5**, 3160 (2014)
Blanco-Redondo et al. *Optica* **1**, 299-306 (2014)

PART 2:
TOPOLOGICAL QUANTUM PHOTONICS







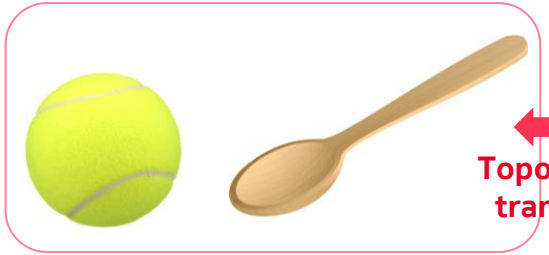


Doyle et al. (in preparation)
Khan et al. *Advanced Materials Technologies*, 2100252 (2021)
Blanco-Redondo**,** *Proceedings of the IEEE* **108,** 837-849 (2020)
Wang et al. *Nanophotonics* **8**, 1327–1335 (2019)
Blanco-Redondo et al. *Science* **362,** 568-571 (2018)
Blanco-Redondo et al. *Phys. Rev. Lett.* **116,** 163901 (2016)

What is topology?

Topologies – quantities that DO NOT CHANGE when we CONTINUOSLY deform a geometric object

genus = 0



genus = 1

genus = 2

Topological transition

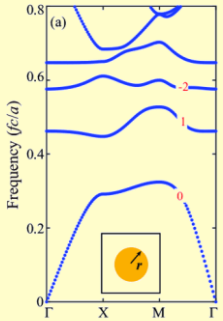
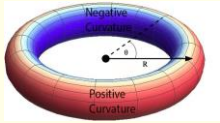
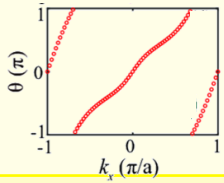
Topological transition

Topological equivalent

Number of holes preserved under continuous deformation

 # holes = genus = topology

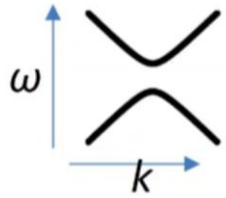
Topology in geometric objects (real space) vs in photonic systems (momentum space)

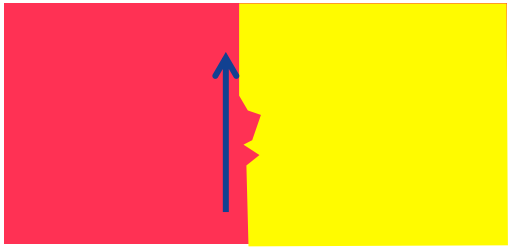
Real Space	**Momentum space**
Geometric objects  	Photonic bands 
Gaussian curvature $K(r) = 1/R^2$  	Berry curvature $\mathcal{F}(\mathbf{k}) = \nabla_{\mathbf{k}} \times \mathcal{A}(\mathbf{k})$ 
Genus (Number of holes) $\frac{1}{2\pi}\int_{\text{surface}} \mathcal{K} dA = 2(1-g)$ 	Chern number (Number of twists/untwists) $C = \frac{1}{2\pi}\oiint \mathcal{F}(\mathbf{k}) \cdot d\mathbf{s}$ 

Topological edge states in photonic systems

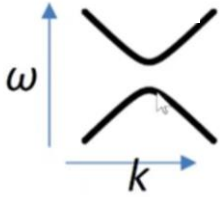
- ✓ Topological invariant (Chern number or Zak Phase) can only take integer values
- ✓ Topological invariant of gapped systems (insulators) cannot change without closing the gap
  → Topological phase transition

$$C = \frac{1}{2\pi} \oiint \mathcal{F}(\mathbf{k}) \cdot d\mathbf{s} = 0$$

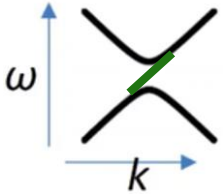




$$C = \frac{1}{2\pi} \oiint \mathcal{F}(\mathbf{k}) \cdot d\mathbf{s} = 1$$



Unidirectional, gapless states at the interface between two materials with different topological invariants



Our topological platform:

A silicon photonics implementation of the SSH model

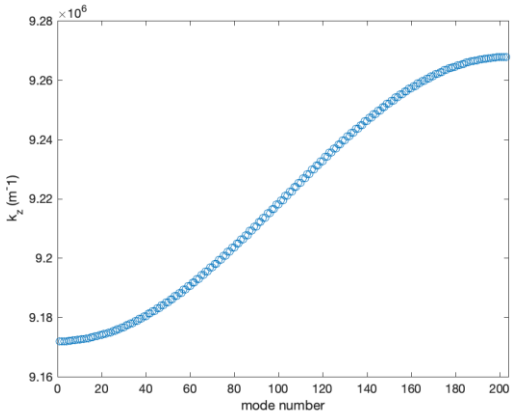
Blanco-Redondo, et al., *Phys. Rev. Lett.* **116,** 163901 (2016)

Other SSH implementations:
Su, **S**chrieffer, and **H**eeger, PRL (1979)
Malkova et al. Opt. Lett. (2009)
Zeuner et al. PRL (2015)
Poli et al. Nat. Comm. (2015)

Relevant topological invariant – Zak phase:

$$\mathcal{Z} = i \oint dq \langle u_q | \partial_q u_q \rangle$$

Zak, PRL 62, 2747 (1989)

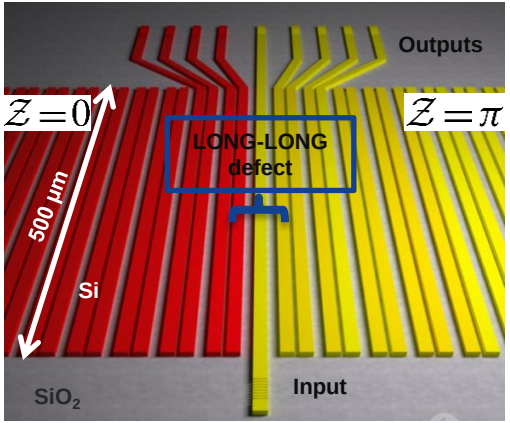


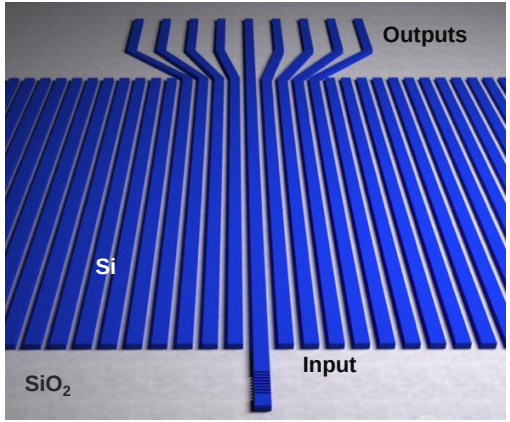
Si waveguides:

- width: w = 450 nm
- height: h = 220 nm
- length: L = 500 μm

Gaps:

- 166 nm
- 294 nm





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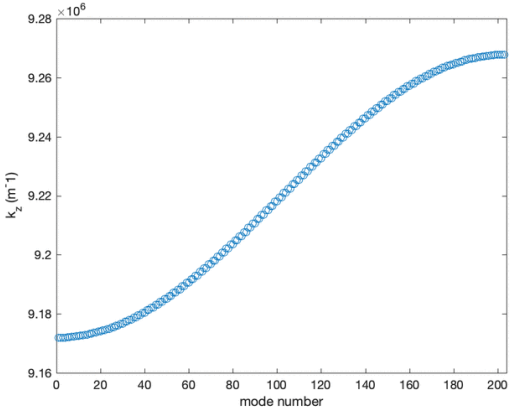
Blanco-Redondo, et al., *Phys. Rev. Lett.* **116,** 163901 (2016)

From equidistant to SSH:



Blanco-Redondo, et al., *Phys. Rev. Lett.* **116,** 163901 (2016)

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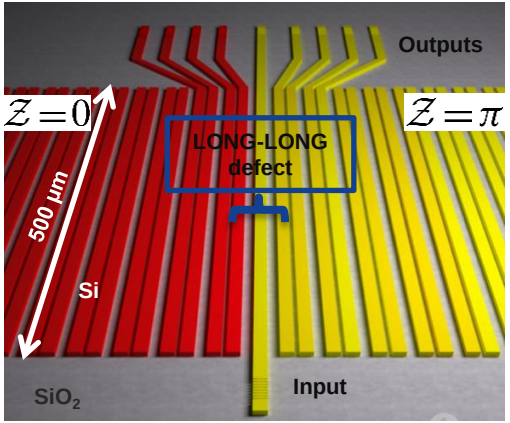

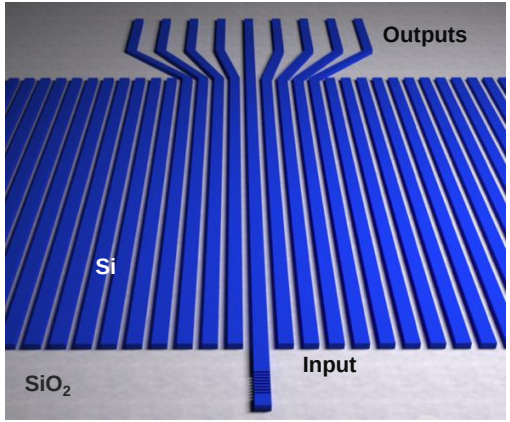

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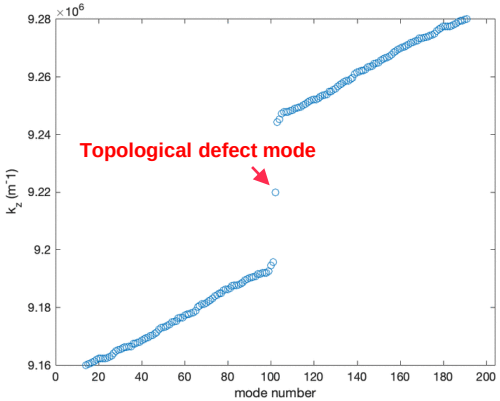
Random disorder in waveguides positions:



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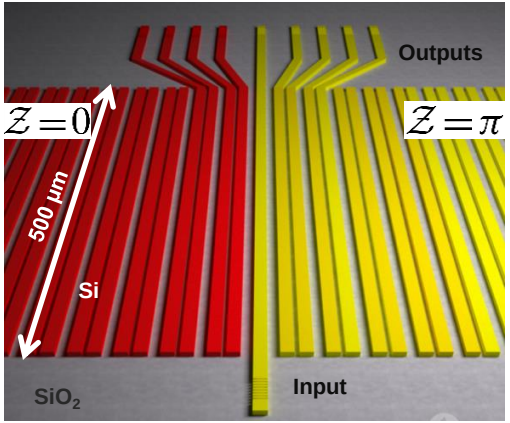

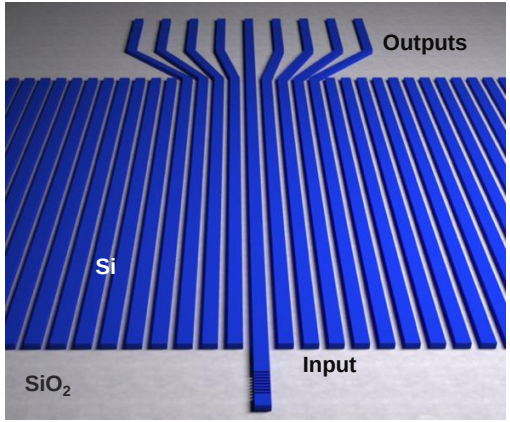

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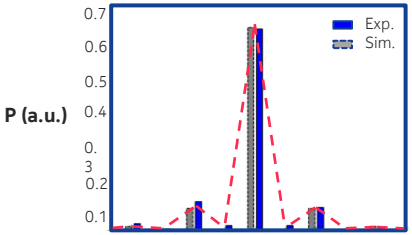
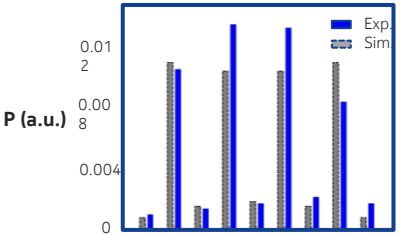
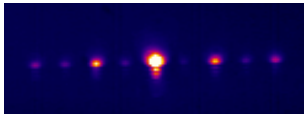
Topological localization

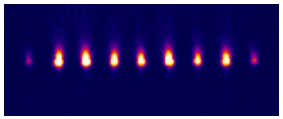


No localization - Discrete diffraction



NIR images





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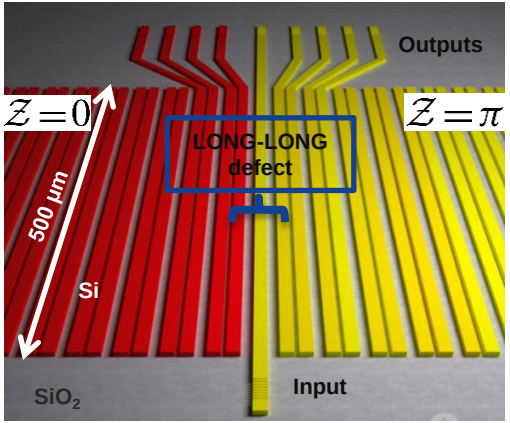

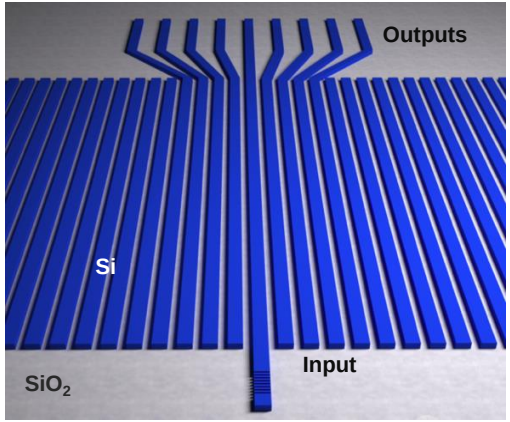

Topological quantum experiments on-chip

Can topology protect photonic quantum states?

Ref.	Geometry	Material	Model	Generation of quantum state	Quantum state	Topologically protected features	
Barik et al. *Science* 359,666-668, 2018	2D photonic crystals	GaAs	QSH	InGaAs quantum dots	Single photon	Unidirectional single-photon transport	M. Hafezi's group (JQI, Maryland)
Mittal et al. *Nature* 561, 502-506,2018	2D coupled resonator array	Si	QSH	SFWM on-chip	Correlated photon pairs	Spectral correlations	
Blanco-Redondo et al. *Science* 372, 568-571,2018	1D waveguide (wg) array	Si	SSH	SFWM on-chip	Correlated photon pairs	Spatial biphoton correlation	**Our work**
M. Wang et al. *Nanophotonics* 8, 1327–1335, 2019	1D wg. array	Si	SSH	SFWM on-chip	Path-entangled states	Path-entangled biphoton correlation	
Tambasco et al. *Science Adv.* 4, eaat3187, 2018	1D wg. array	Borosilicate	AAH	SPDC off-chip	Heralded single photon	High-visibility quantum interference	A. Peruzzo's group (RMIT)
Y. Wang et al. *PRL* 122, 193903, 2019	1D wg. array	Borosilicate	SSH	SPDC off-chip	Heralded single photon	Second-order anti-correlation	Xianmin Jin's group (SJTU, Shanghai)
Y. Wang et al. *Optica* 6, 955-960, 2019	1D wg. array	Borosilicate	AAH	SPDC off-chip	Correlated photon pairs	Cross-correlation function	
Y. Wang et al. arXiv:1903.03015	1D wg. array	Borosilicate	SSH	SPDC off-chip	Polarization entangled states	High-concurrence and high-purity	

Review paper: A. Blanco-Redondo, "Topological Nanophotonics: Toward Robust Quantum Circuits," in *Proceedings of the IEEE* 108 (5), pp. 837-849, 2020

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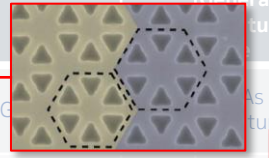

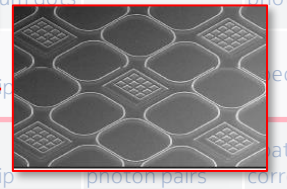

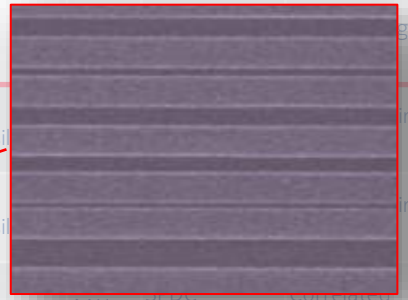

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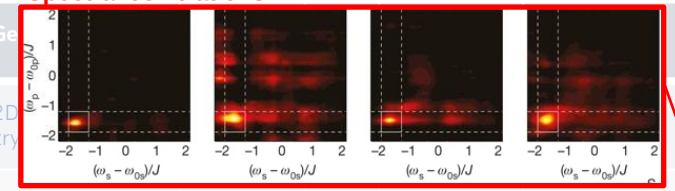
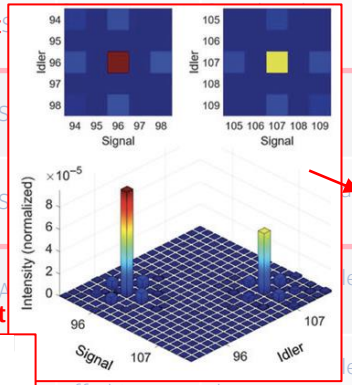
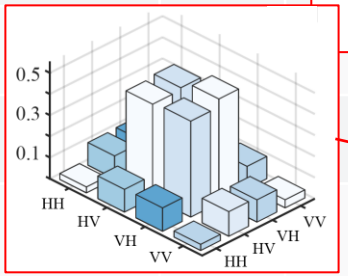
Spectral correlations



Path entanglement



Polarization entanglement



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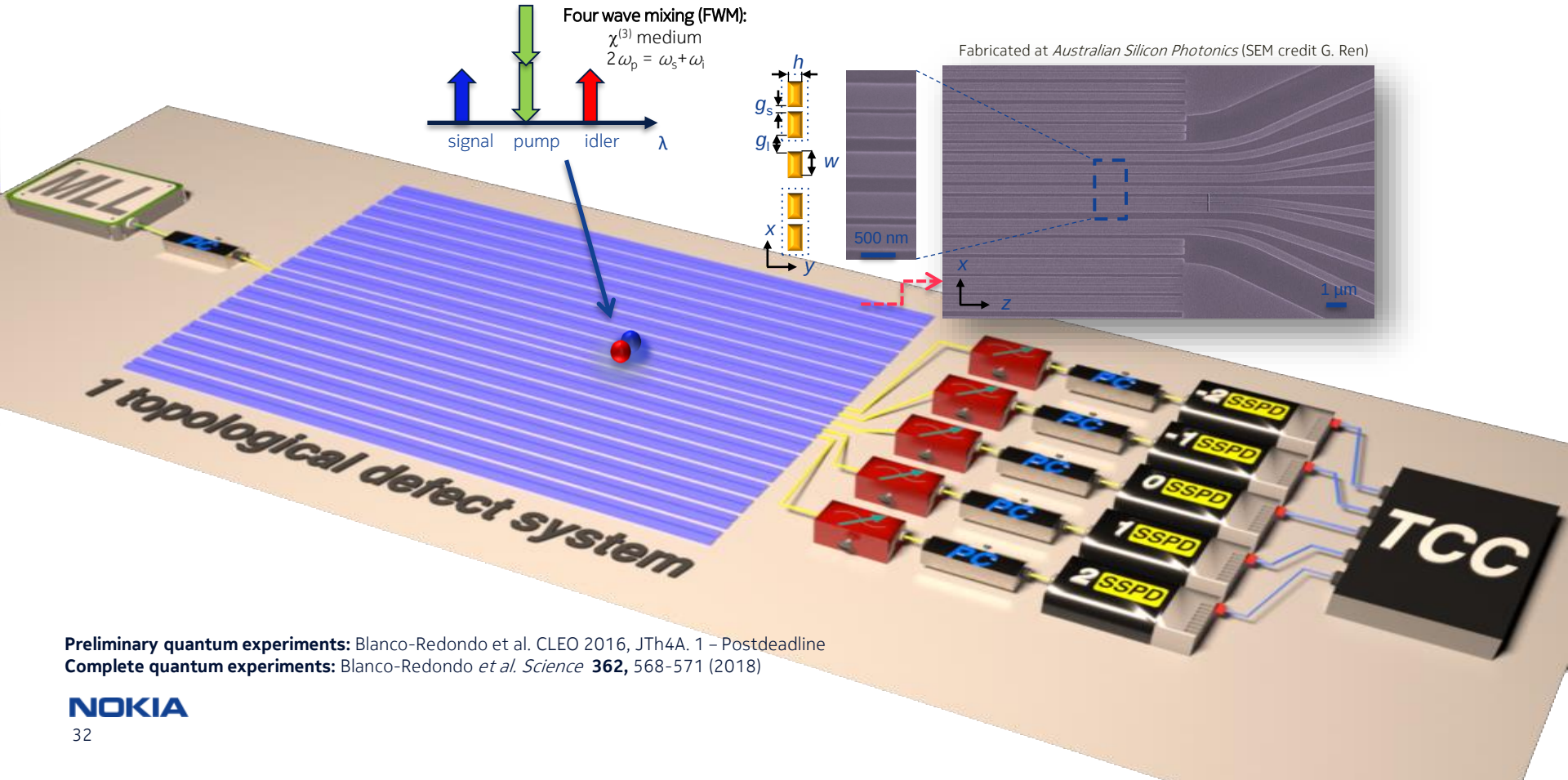
Y. Wang et al. arXiv:1903.03015	1D			SPDC off-chip	Polarization entangled states	High-concurrence and high-purity	

Review paper: A. Blanco-Redondo, "Topological Nanophotonics: Toward Robust Quantum Circuits," in *Proceedings of the IEEE* 108 (5), pp. 837-849, 2020

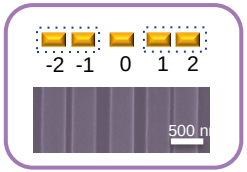
Topological protection of biphoton states



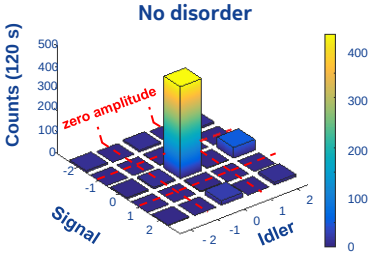
Preliminary quantum experiments: Blanco-Redondo et al. CLEO 2016, JTh4A. 1 – Postdeadline
Complete quantum experiments: Blanco-Redondo *et al. Science* **362,** 568-571 (2018)

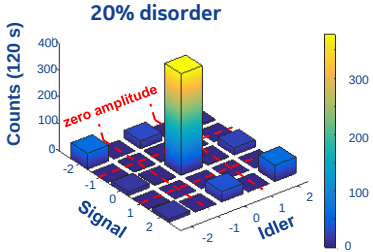
Measuring the biphoton correlation at the output of our topological lattice

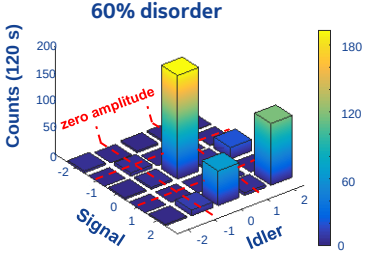
TOPOLOGICAL lattice

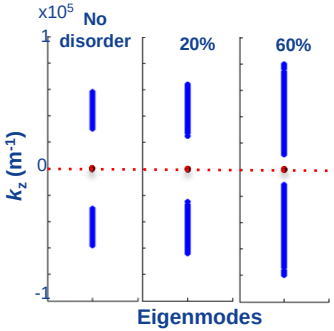


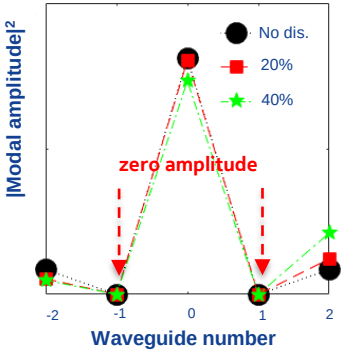
Blanco-Redondo, Bell, Oren, Eggleton & Segev, ***Science*** 362, 568-571 (2018)





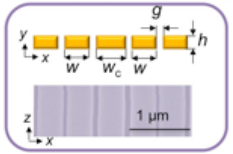




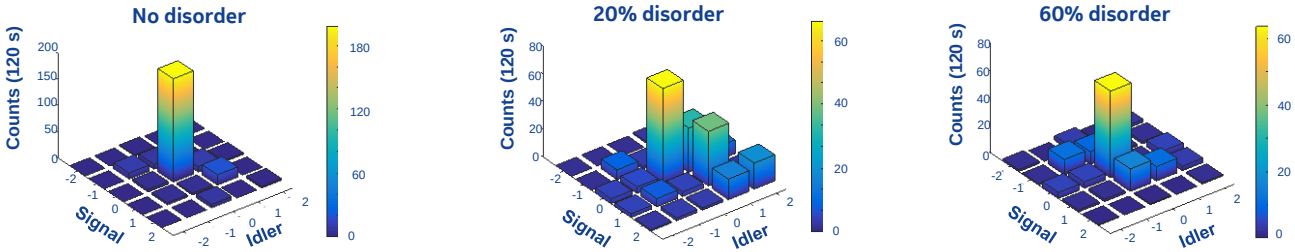


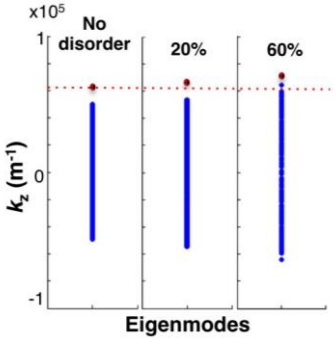
Measuring the biphoton correlation at the output of our trivial lattice

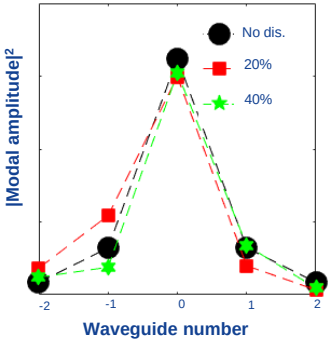
TRIVIAL lattice



Blanco-Redondo, Bell, Oren, Eggleton & Segev, ***Science*** 362, 568-571 (2018)

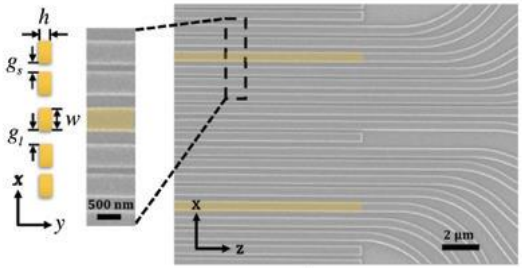






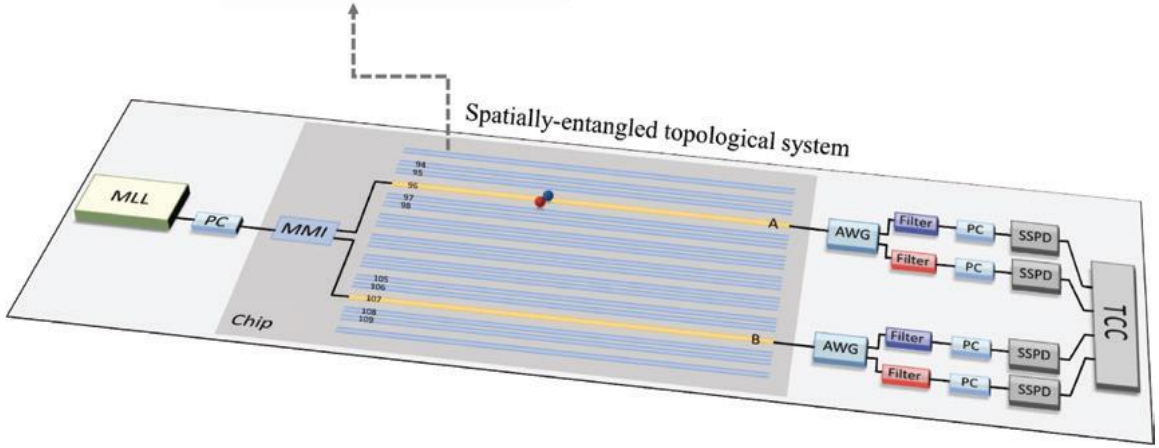
Path-entanglement between topological modes

Spatially-entangled topological system



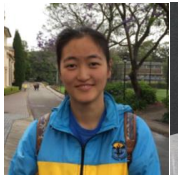
$$|\psi\rangle = \frac{|1_s 1_i\rangle_A |0_s 0_i\rangle_B + e^{2i\phi} |0_s 0_i\rangle_A |1_s 1_i\rangle_B}{\sqrt{2}}$$

Silverstone et al. Nature Photonics 8, 104 (2014)

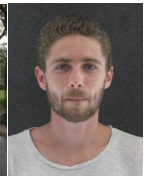


M. Wang, C. Doyle, B. Bell, M. J. Collins, E. Magi, B. J. Eggleton, M. Segev, and A. Blanco-Redondo, ***Nanophotonics*** *8, 1327–1335,* 2019

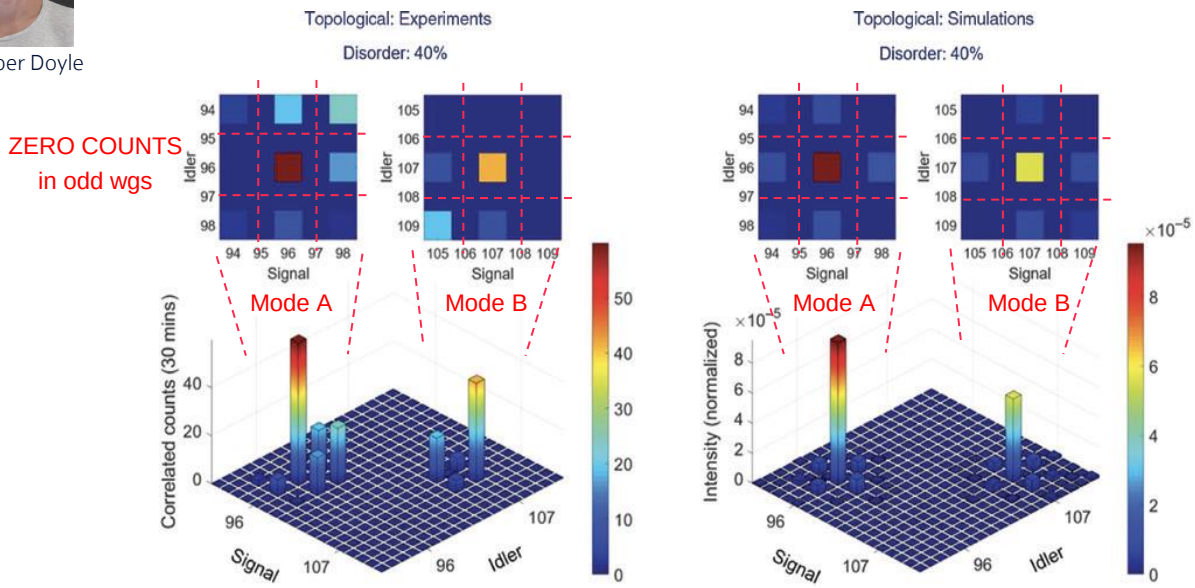
Path-entanglement between topological modes



Michelle Wang



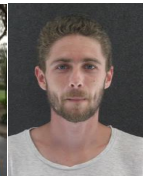
Cooper Doyle



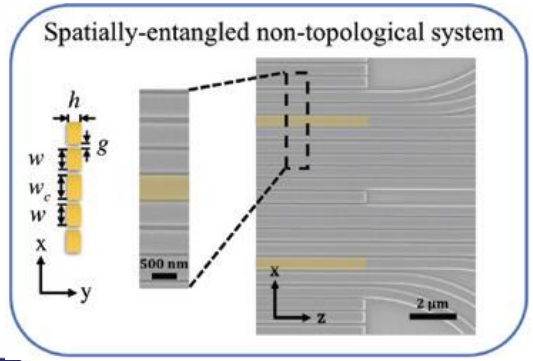
M. Wang, C. Doyle, B. Bell, M. J. Collins, E. Magi, B. J. Eggleton, M. Segev, and A. Blanco-Redondo, ***Nanophotonics*** *8, 1327–1335,* 2019

Path-entanglement between trivial modes

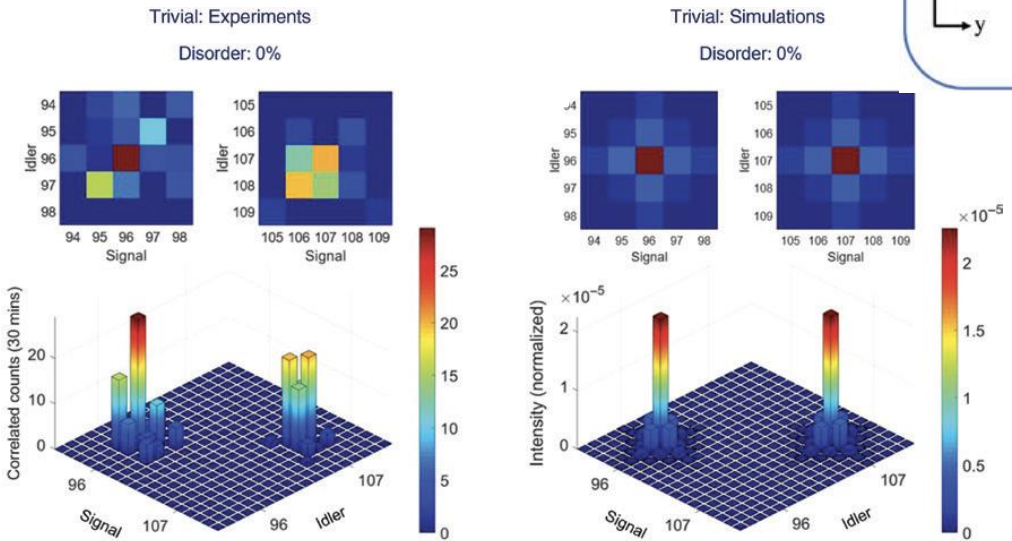
Michelle Wang



Cooper Doyle

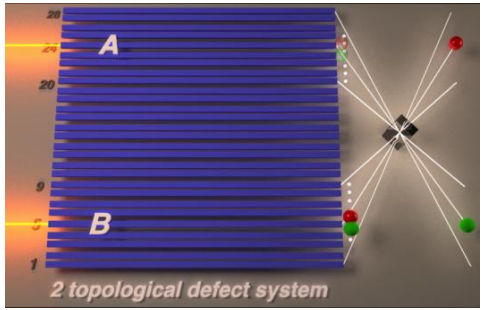


No protected feature



M. Wang, C. Doyle, B. Bell, M. J. Collins, E. Magi, B. J. Eggleton, M. Segev, and A. Blanco-Redondo, ***Nanophotonics*** *8, 1327–1335,* 2019

Probing path-entanglement robustness by quantum interference (simulations)



Before the interferometer:

$$|\psi\rangle = \frac{|A\rangle_s |A\rangle_t + e^{2i\phi} |B\rangle_s |B\rangle_t}{\sqrt{2}}$$

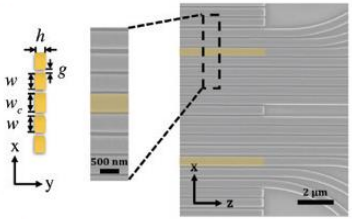
After the interferometer:

$$|\psi_{\text{bunch}}\rangle = \frac{i}{\sqrt{2}}(|B\rangle_s |B\rangle_t - |A\rangle_s |A\rangle_t)$$

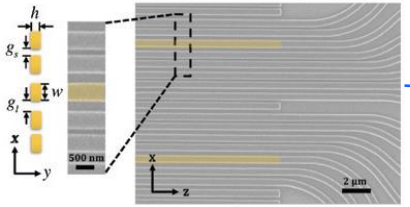
$$|\psi_{\text{split}}\rangle = \frac{i}{\sqrt{2}}(|A\rangle_s |B\rangle_t + |B\rangle_s |A\rangle_t)$$

$$|\psi_{\text{out}}\rangle = \cos\phi\,|\psi_{\text{split}}\rangle + \sin\phi\,|\psi_{\text{bunch}}\rangle$$

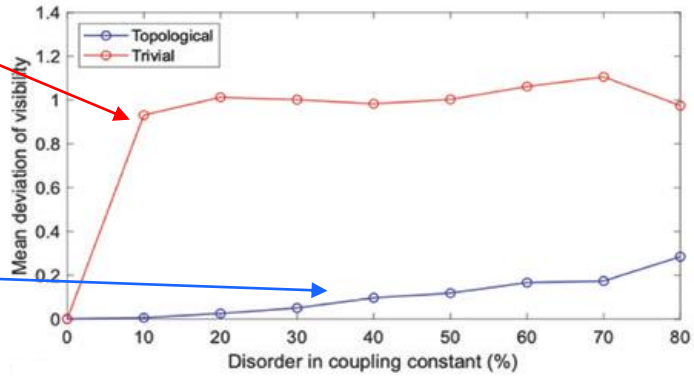
Spatially-entangled non-topological system



Spatially-entangled topological system

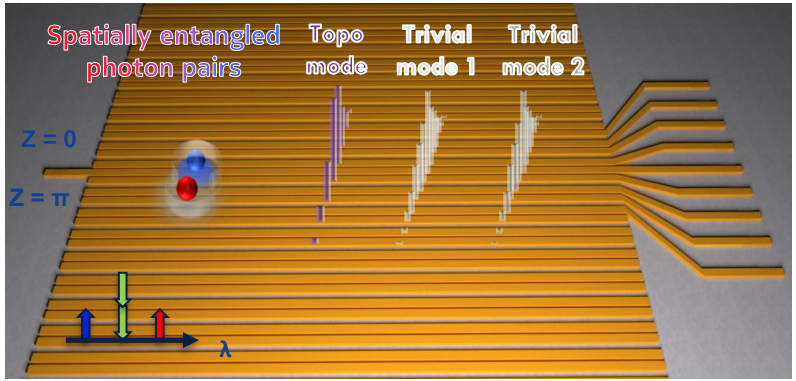


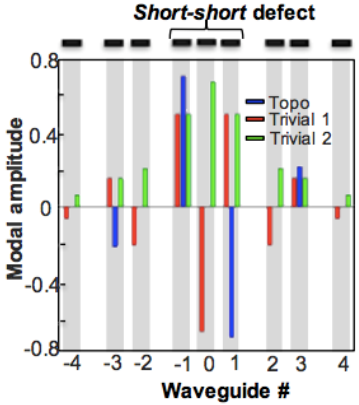
$$\text{Visibility} = \frac{\cos^2\phi - \sin^2\phi}{\cos^2\phi + \sin^2\phi} = \cos 2\phi$$

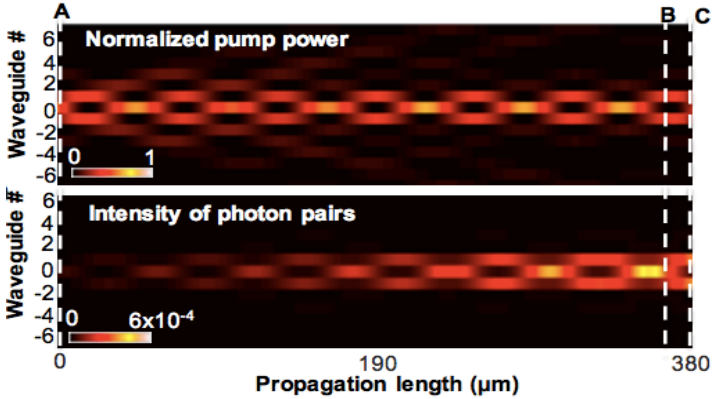


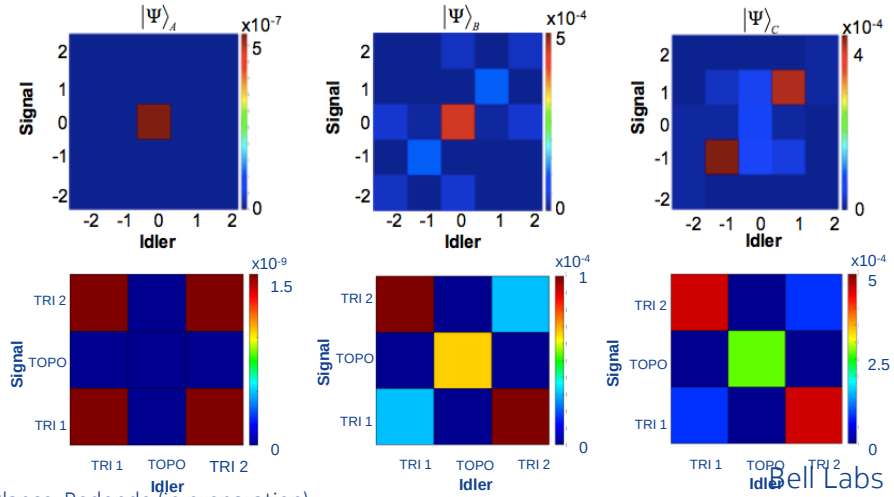
M. Wang, C. Doyle, B. Bell, M. J. Collins, E. Magi, B. J. Eggleton, M. Segev, and A. Blanco-Redondo, ***Nanophotonics*** *8, 1327–1335,* 2019

Entanglement between topological and trivial modes









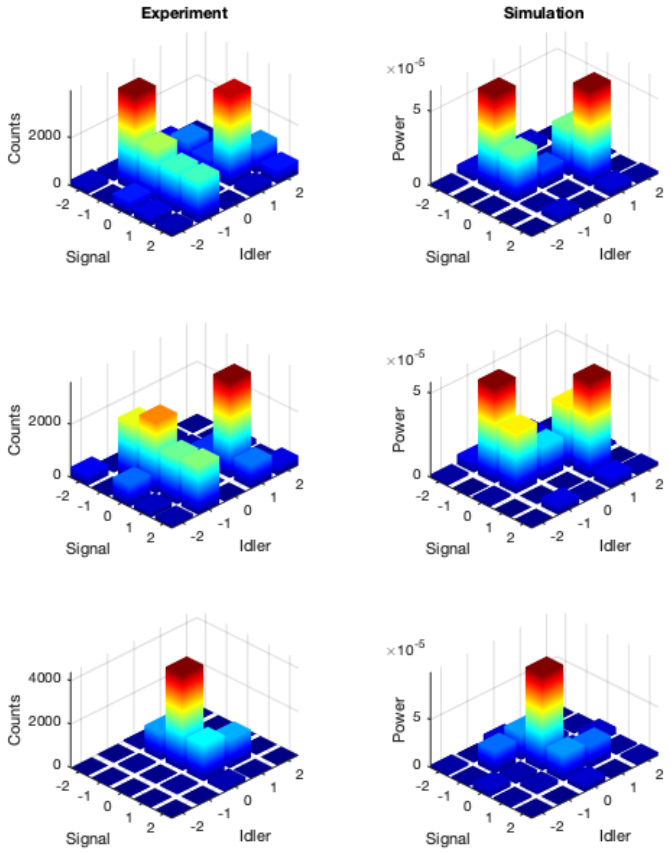
Doyle, Zhang, Wang, Bell, Bartlett, and Blanco-Redondo (in preparation)

Entanglement between topological and trivial modes

No disorder

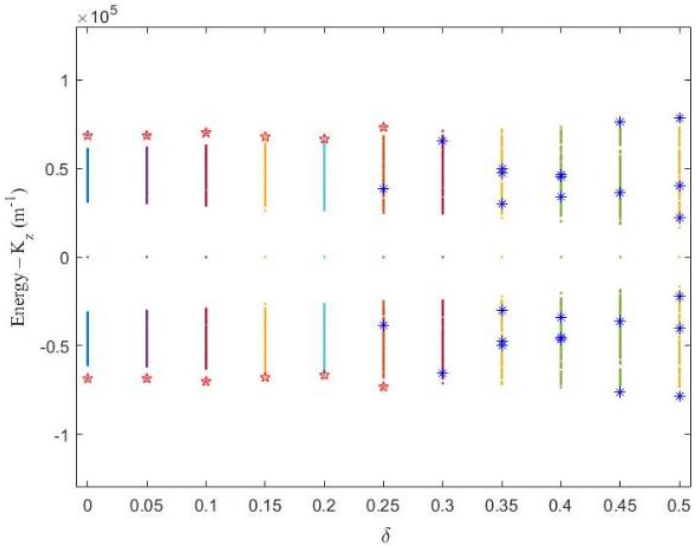
20% disorder

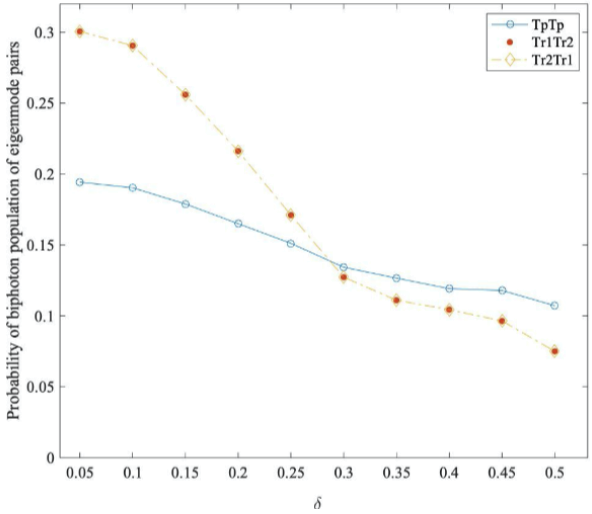
40% disorder



Doyle, Zhang, Wang, Bell, Bartlett, and Blanco-Redondo (in preparation)

Entanglement between topological and trivial modes



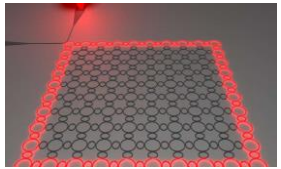


Doyle, Zhang, Wang, Bell, Bartlett, and Blanco-Redondo (in preparation)

End of Part 2:
Conclusions

✓ Topological photonics is moving towards applications

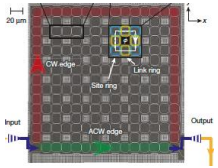
Topological lasers



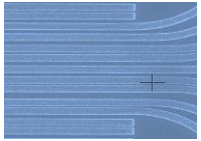
Topological quantum photonics

✓ Topology can protect quantum information

Spectral correlations

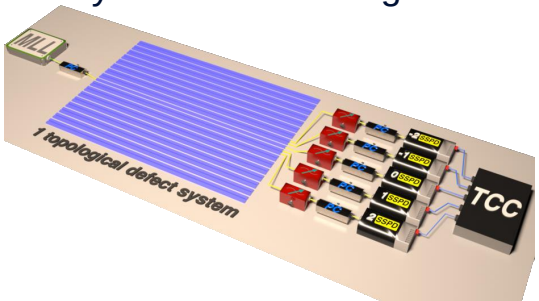


Path entanglement



Polarization entanglement

✓ Arrays of silicon waveguides to test topological quantum concepts



CMOS compatible

On-chip generation of quantum states

Convenient coupling, low loss, room temp. …

Thank you!

andrea.blanco-redondo@Nokia-bell-labs.com

NOKIA Bell Labs

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School of physics

Australian Government
Australian Research Council

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