Simulation of Vector Mode Grating Coupler Interfaces for Integrated Optics

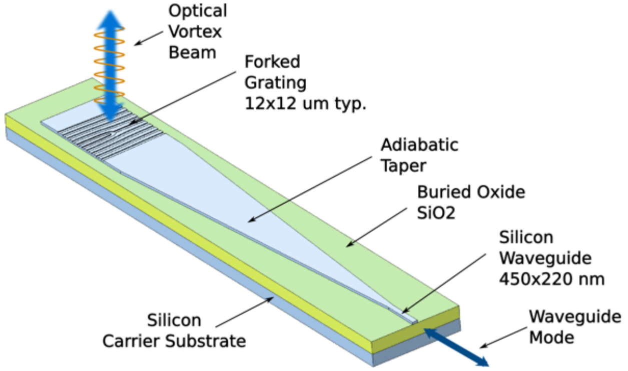
Chris Nadovich

Clarkson
UNIVERSITY

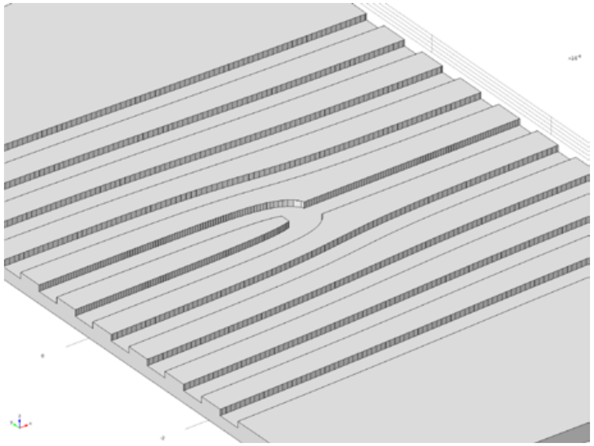
COMSOL
CONFERENCE
2015 BOSTON

Research Objective

The novel combination of a forked holographic grating with a Bragg coupler structure to create a new device: The Forked Grating Coupler (FGC)



- Not previously reported in the literature
- Selectively and efficiently couples vortex beams to or from dielectric waveguide “wires” of a photonic integrated circuit.
- Replaces today’s bulk optics vortex interfaces with a micron-scale integrated device.
- Targeted at an anticipated future need of the optical communications industry and other developing optical vortex applications.

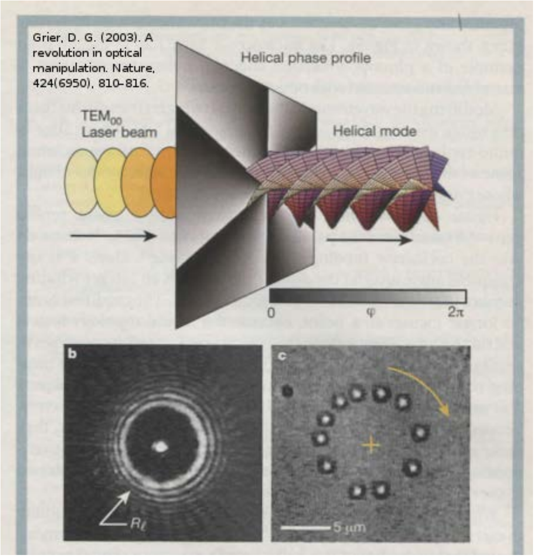


The nature of the Forked Grating Coupler ties together two distinct concepts: optical vortices, and grating couplers for integrated optics.

BACKGROUND

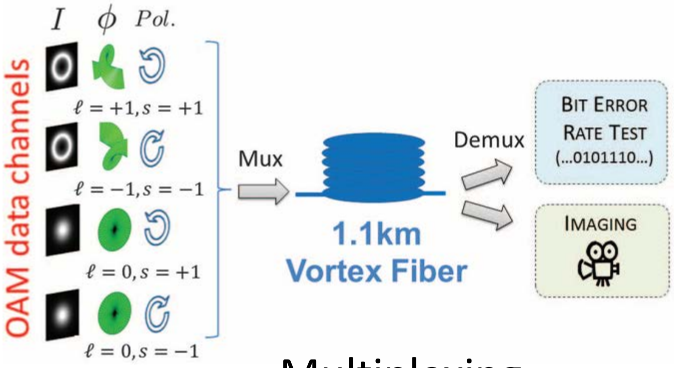
Introduction to Optical Vorticies

- General theory of phase singularities in wave physics introduced by Nye and Berry (1974).
- Phase singularities occur in “optical vortex” (OV) light beams
- OV beams possessing optical orbital angular momentum (OAM).
- OV beams have many practical applications



Grier, D. G. (2003). A revolution in optical manipulation. Nature, 424(6950), 810–816.

Optical Tweezers



Multiplexing

Bozinovic et al. Terabit-scale Orbital Angular Momentum Mode Division Multiplexing in Fibers. Science, Vol 340 (2013)

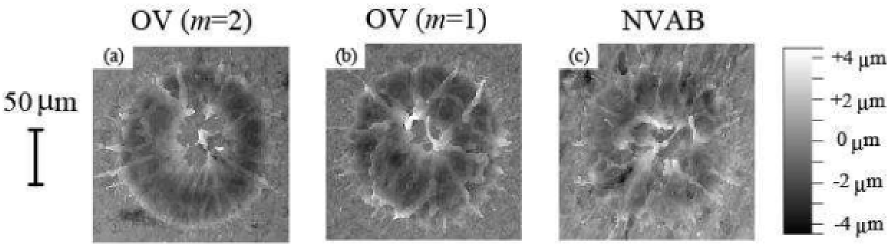


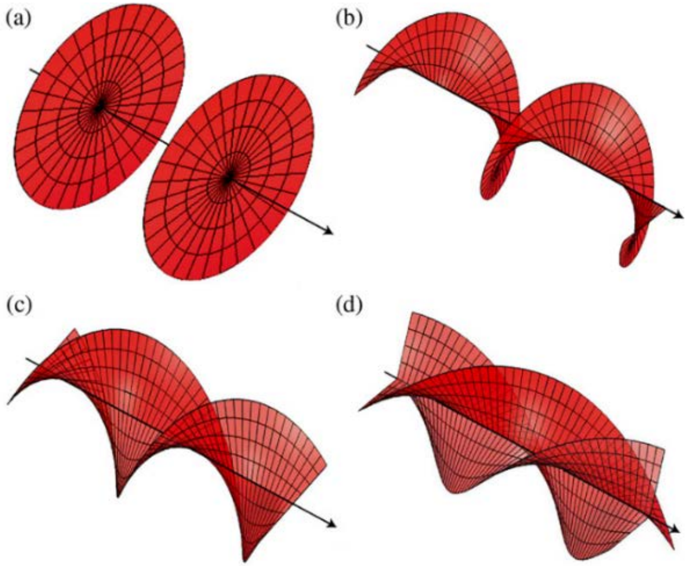
Fig. 2. Laser microscope images of processed surfaces for (a) the OV with $m = 2$ (b) OV with $m = 1$, and (c) NVAB with incident energy of 3 mJ/pulse, respectively. Dotted circles denote debris.

Hamazaki, J., Morita, R., Chujo, K., Kobayashi, Y., Tanda, S., & Omatsu, T. (2010). Optical-vortex laser ablation. Optics Express, 18(3), 2144–51.

Laser Ablation

Vortex Modes

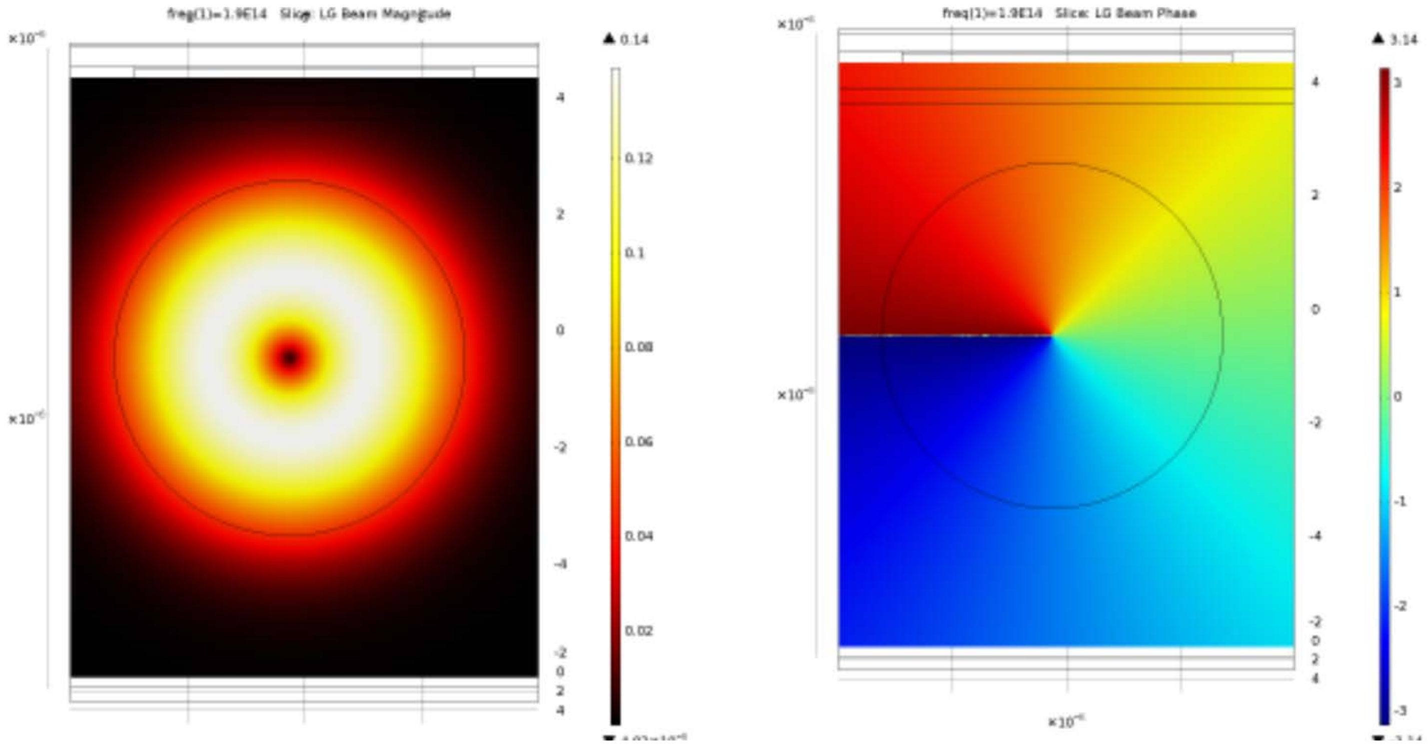
1. Optical Vortex (OV) beams have an azimuthal phase dependence exp($i \chi \varphi$) where χ represents the *topological charge* of the Orbital Angular Momentum (OAM).
2. The Poynting vector has an azimuthal component resulting in helical phase fronts.
3. E fields cancel at center giving rise to optical vorticies – zero intensity centers.
4. Polarization is a characteristic of the beam independent of OAM.
5. OV modes propigate in free space or in special kinds of optical fiber.



Helical phase fronts for l = 0 to l = 3 (a-d respectively)

Alison M. Yao and Miles J. Padgett, "Orbital angular momentum: origins, behavior and applications", Advances in Optics and Photonics 3, 161-204, 2011

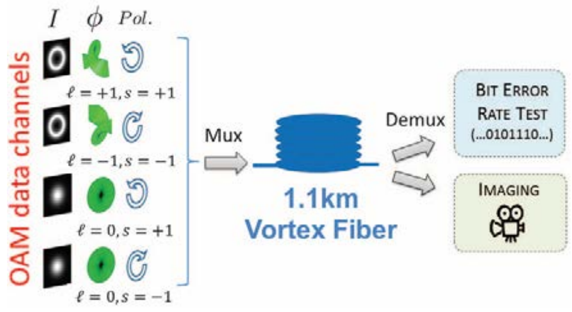
Beam Amplitude and Phase

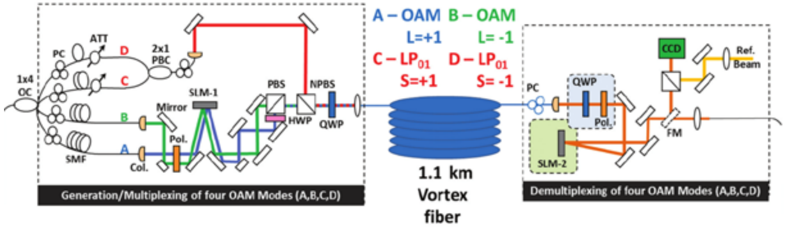


Magnitude (left) and phase of χ = +1 vortex beam cross section.

Vortex Multiplexing

- Multiplexing across a set of OAM "charge" modes has been demonstrated as a viable method to dramatically multiply the capacity of optical fiber.
- OAM multiplexing has been accomplished only with large, bulk optics devices not amenable to direct implementation on a photonic IC.
- Commercially viable OAM will require compact, low cost interfacing with PICs.

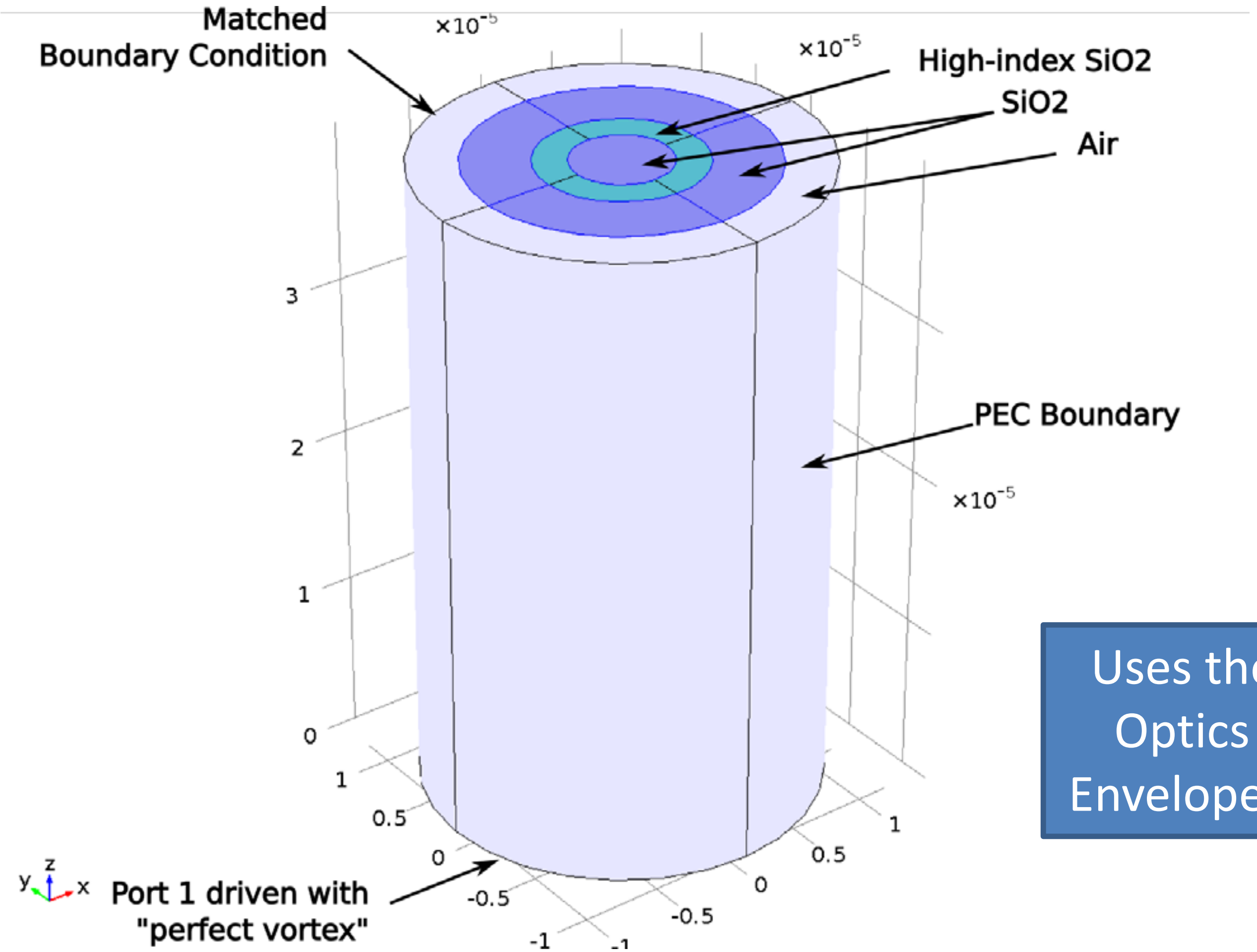




OAM multiplexing accomplished in Vortex Fiber using a large, bulk optics system.

Bozinovic et al. Terabit-scale Orbital Angular Momentum Mode Division Multiplexing in Fibers. Science, Vol 340 (2013)

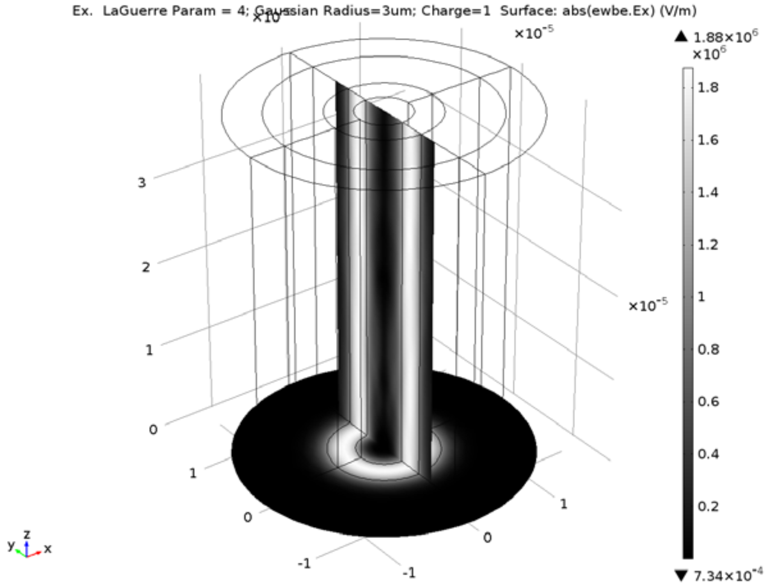
Vortex Fiber Simulation Model

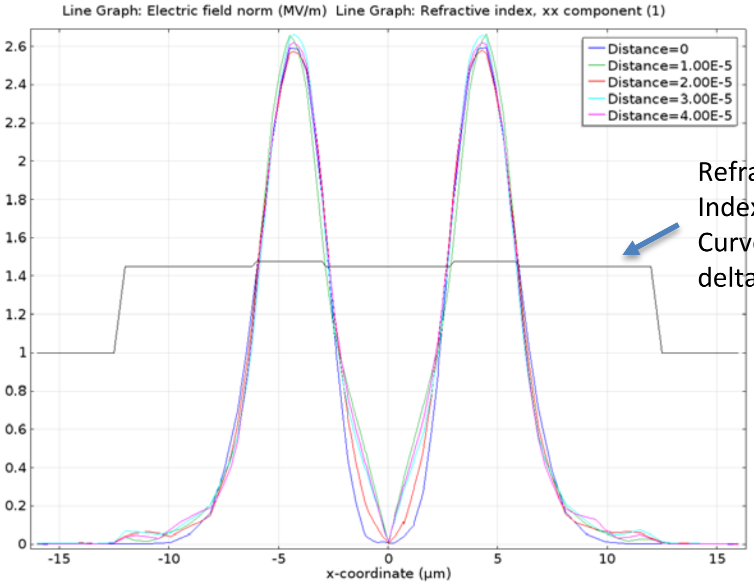


Uses the Wave Optics Beam Envelope Physics

Vortex Fiber Propagation with CP

Plot of E-field magnitude versus transverse (x) coordinate. Distance 0 is the driven end of the fiber. Driving illumination function is modified LG mode that approximates a “perfect” charge = 1 vortex matched to this fiber diameter. Polarization is CP.



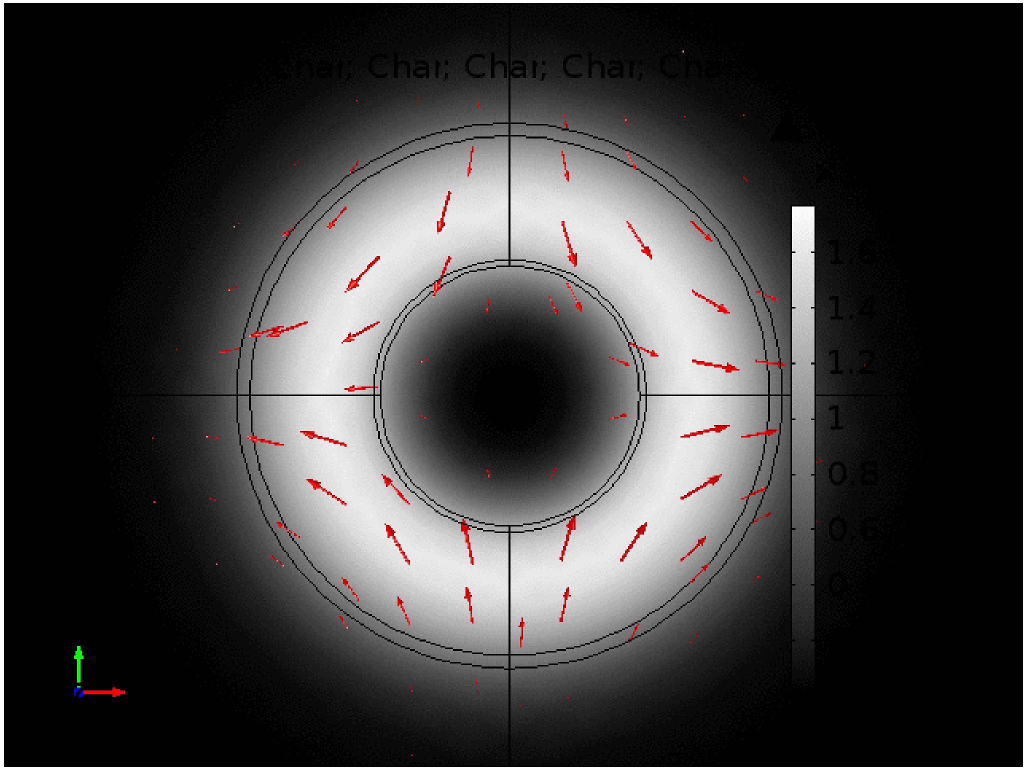


Refractive Index Curve (Index delta=0.025)

Fiber Diameter	24 um
Index Delta	0.025
Index Ring Radius	3-6 um

Circular Polarized Vortex Modes

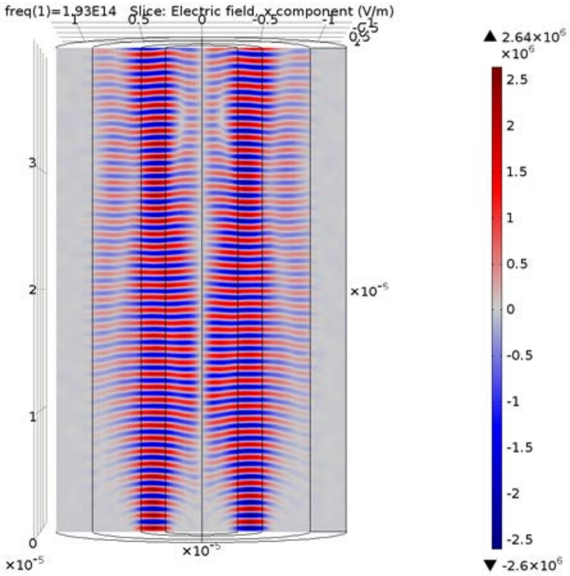
Circular Polarization is stable in the presence of OAM bearing modes



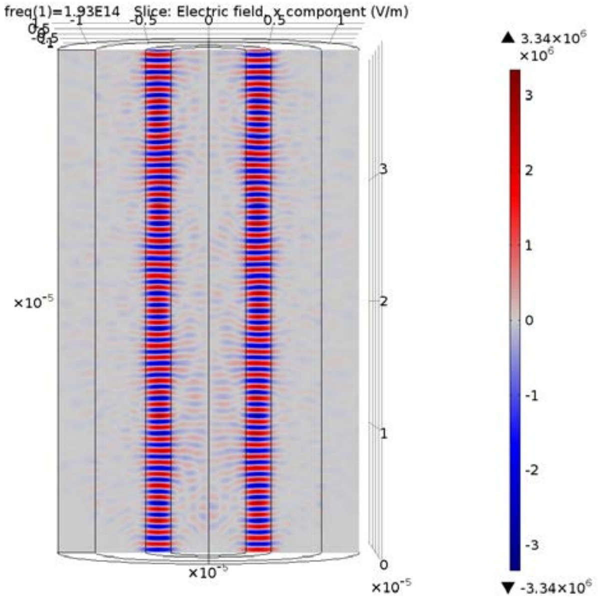
Circular Polarized Charge = 1 OAM beam propagating in step-ring-index fiber

Mode Confinement in Index Ring

Fiber Diameter	18 um
Ring Diameter	6-10 um
OAM	L=+1
Polarization	CP
Mode	“Perfect vortex” with cosine taper

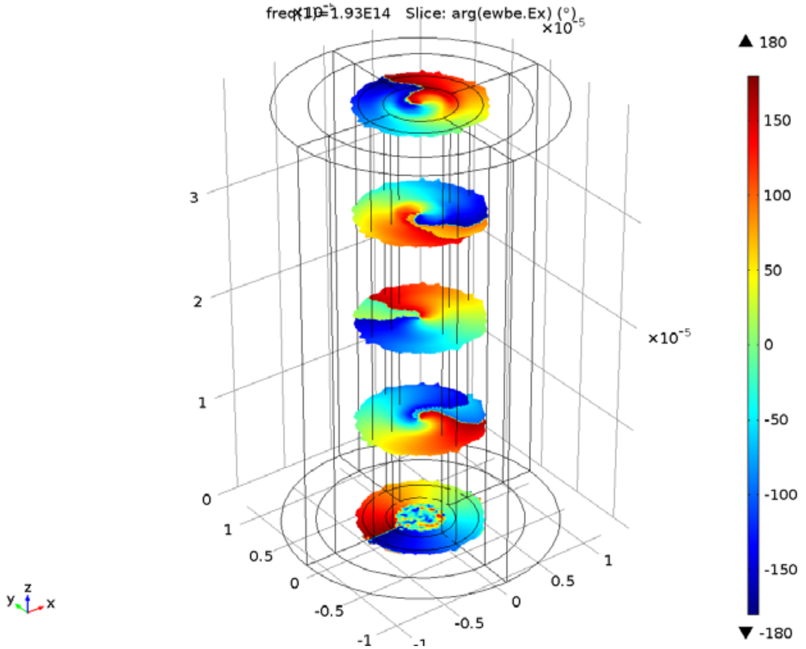


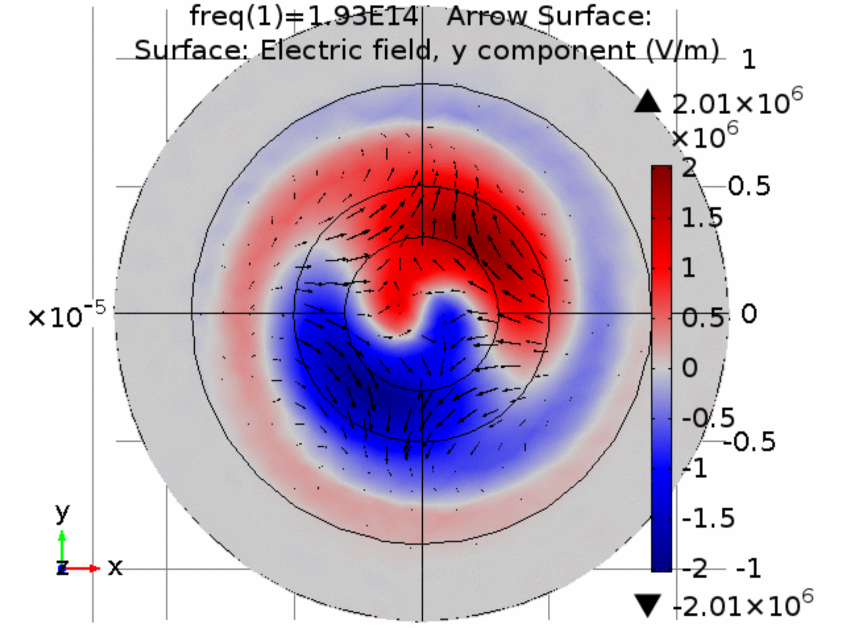
Index Delta: 0.025



Index Delta: 0.25

CP+OAM Mode Phase-Front in Weak Confinement





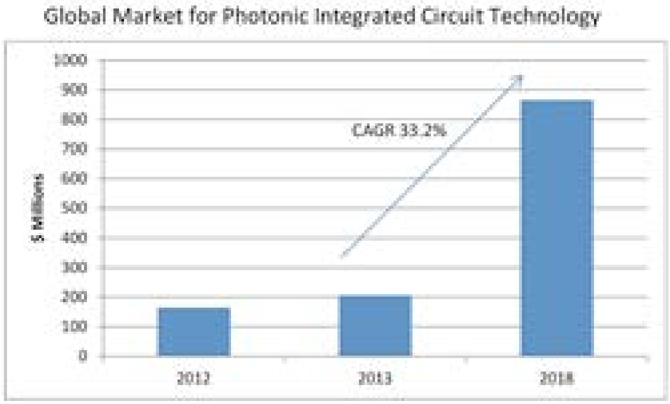
Cut at z=10 um

Fiber Diameter	18 um
Ring Diameter	6-10 um
Index Delta	0.025
OAM	L=+1
Polarization	CP
Mode	“Perfect vortex” with cosine taper

Photonic ICs

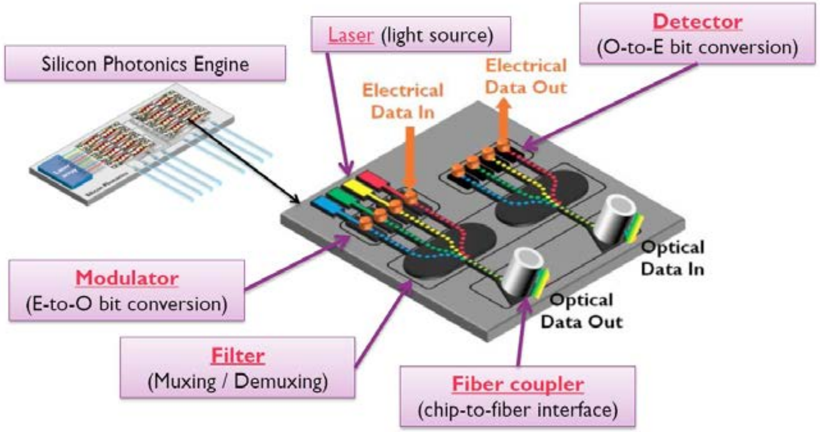
Advantages of PICs:

- Smaller, cheaper, and more stable replacement for bulk optics
- Easily Integrated with electronics (CMOS)
- Resistant to EMI and EMP
- Increased performance



Photonic Integrated Circuits: Technologies and Global Markets, *Report PHO007A*, BCC Research LLC, Wellesley, MA, 2014

The global photonic integrated circuit (IC) technology market is expected to have a compound annual growth rate (CAGR) of 33.2% over the five-year period, 2013 to 2018.



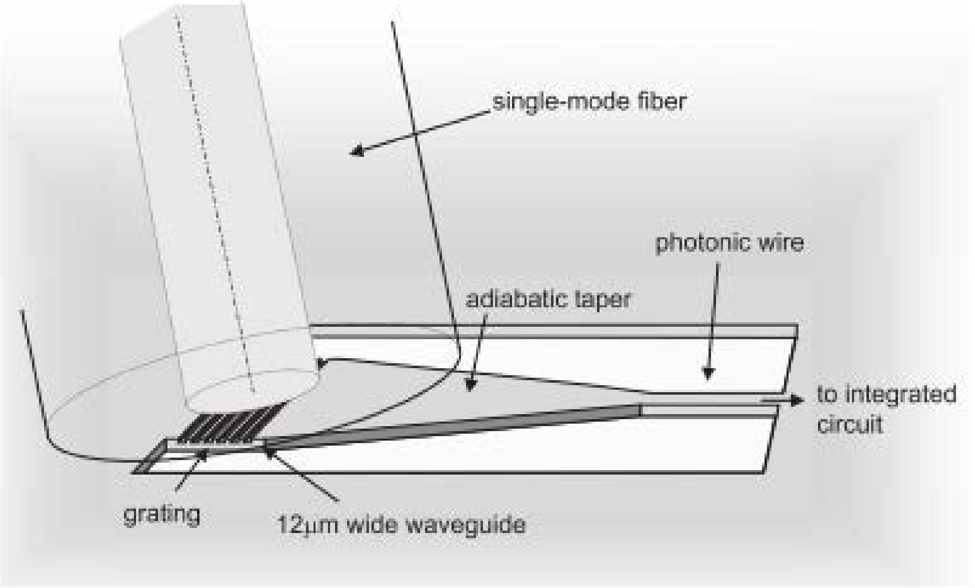
Happich, J, “CMOS-compatible intra-chip photonics brings new class of sensors”, *EE Times Europe*, October 15, 2013

- Grating couplers are standard silicon PIC device library components.
- An OV compatible grating coupler device is a natural choice for a low cost, practical OV beam interface implementation on a PIC.
- Such a device does not currently exist. This research seeks to create it.

Grating Couplers

- Attractive interface from fiber or freespace to photonic IC
  - Well developed technology
  - Theoretical efficiencies approaching 100%
  - Practical efficiencies above 70%
  - Near vertical coupling provides flexibility in placing the optical interface anywhere on the chip surface.
  - Alternative to edge and prism couplers

Existing coupler designs **do not work with OAM beams**



Most “Bragg” coupler simulations done in 2D

Taillaert, Dirk, Frederik Van Laere, Melanie Ayre, Wim Bogaerts, Dries Van Thourhout, Peter Bienstman, and Roel Baets. 2006. “Grating Couplers for Coupling between Optical Fibers and Nanophotonic Waveguides.” Japanese Journal of Applied Physics 45 (8A): 6071–77. doi:10.1143/JJAP.45.6071.

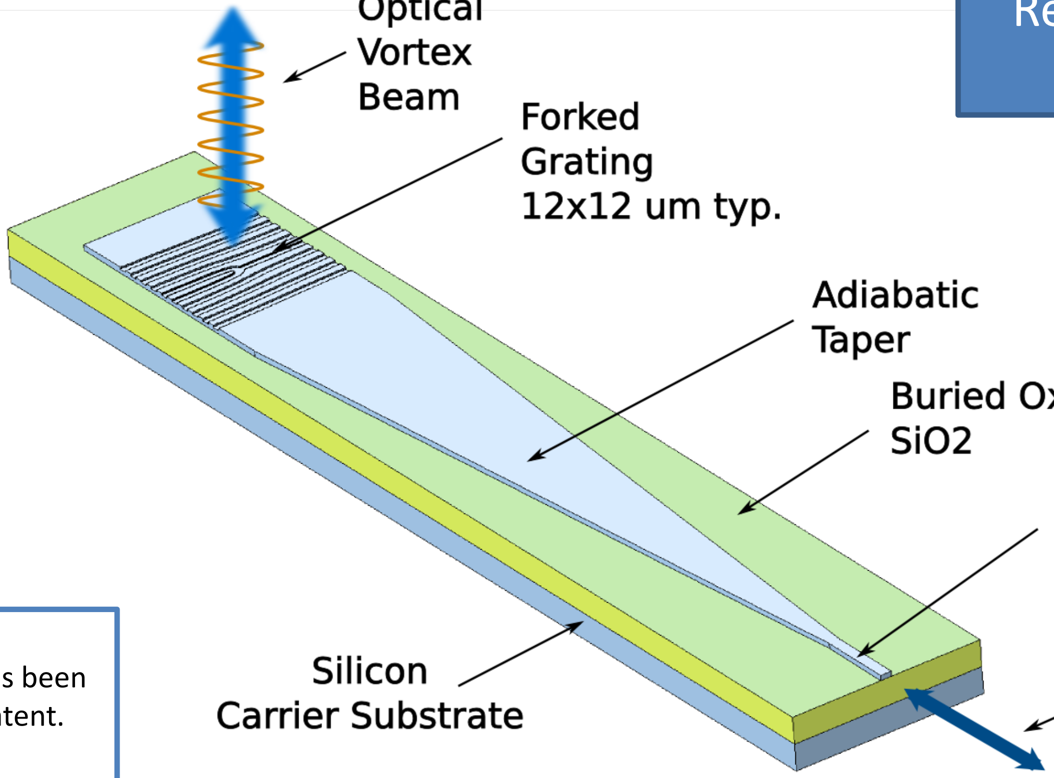
Combining a forked holographic grating with a Bragg coupler structure

FORKED GRATING COUPLER

Forked Grating Coupler

The novel combination of a forked holographic grating with a Bragg coupler structure

Requires 3D Model



Optical Vortex Beam

Forked Grating 12x12 um typ.

Adiabatic Taper

Buried Oxide SiO2

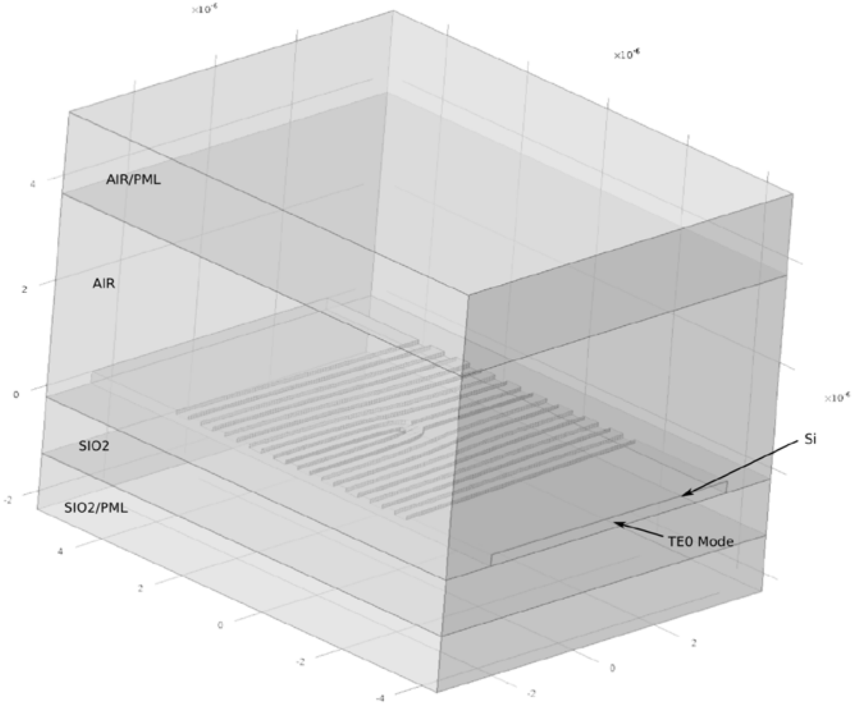
Silicon Waveguide 450x220 nm

Waveguide Mode

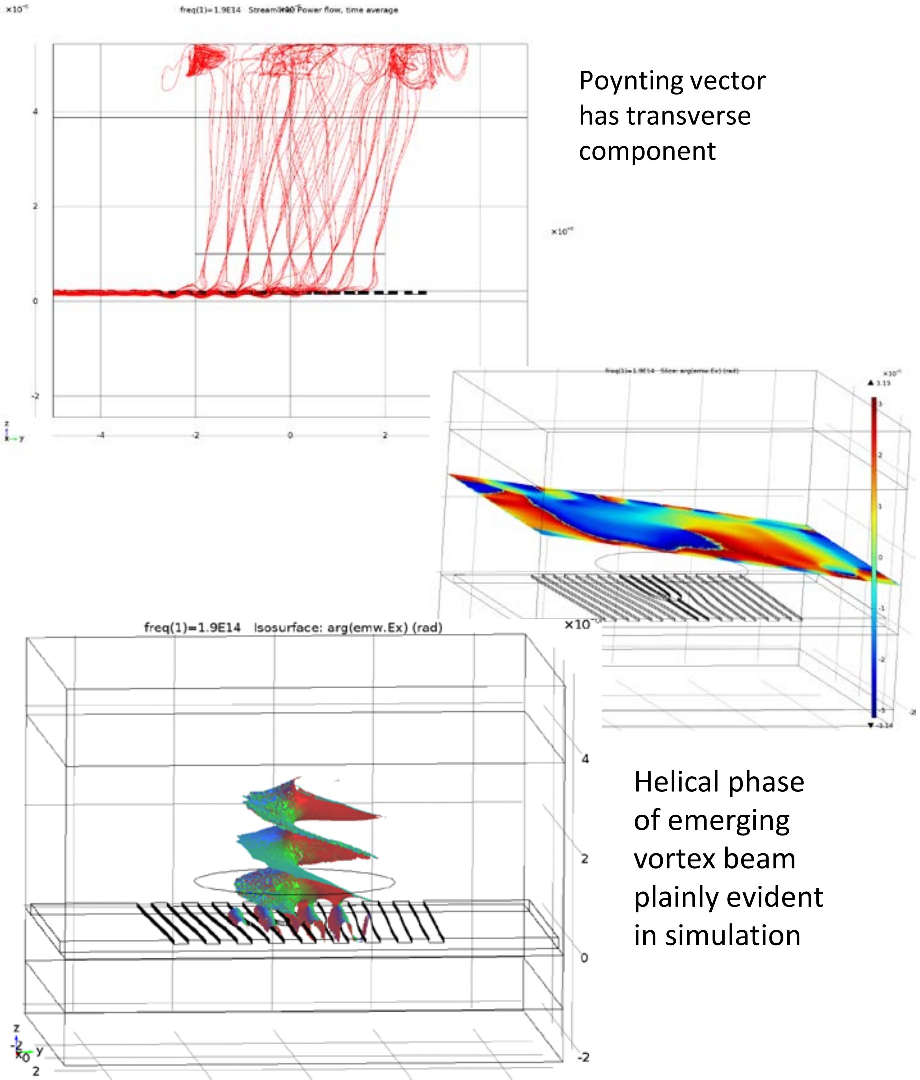
Silicon Carrier Substrate

The Forked Grating Coupler invention described herein has been submitted for a *provisional* patent. The application number is 62/115,668 and the filing date was February 13th 2015.

FGC 3D Modeling



The FGC is 3D modeled in COMSOL as a Si waveguide with grating “grooves” on a SOI wafer. Perfectly Matched Layers (PML) above and below absorb exiting waves.



Poynting vector has transverse component

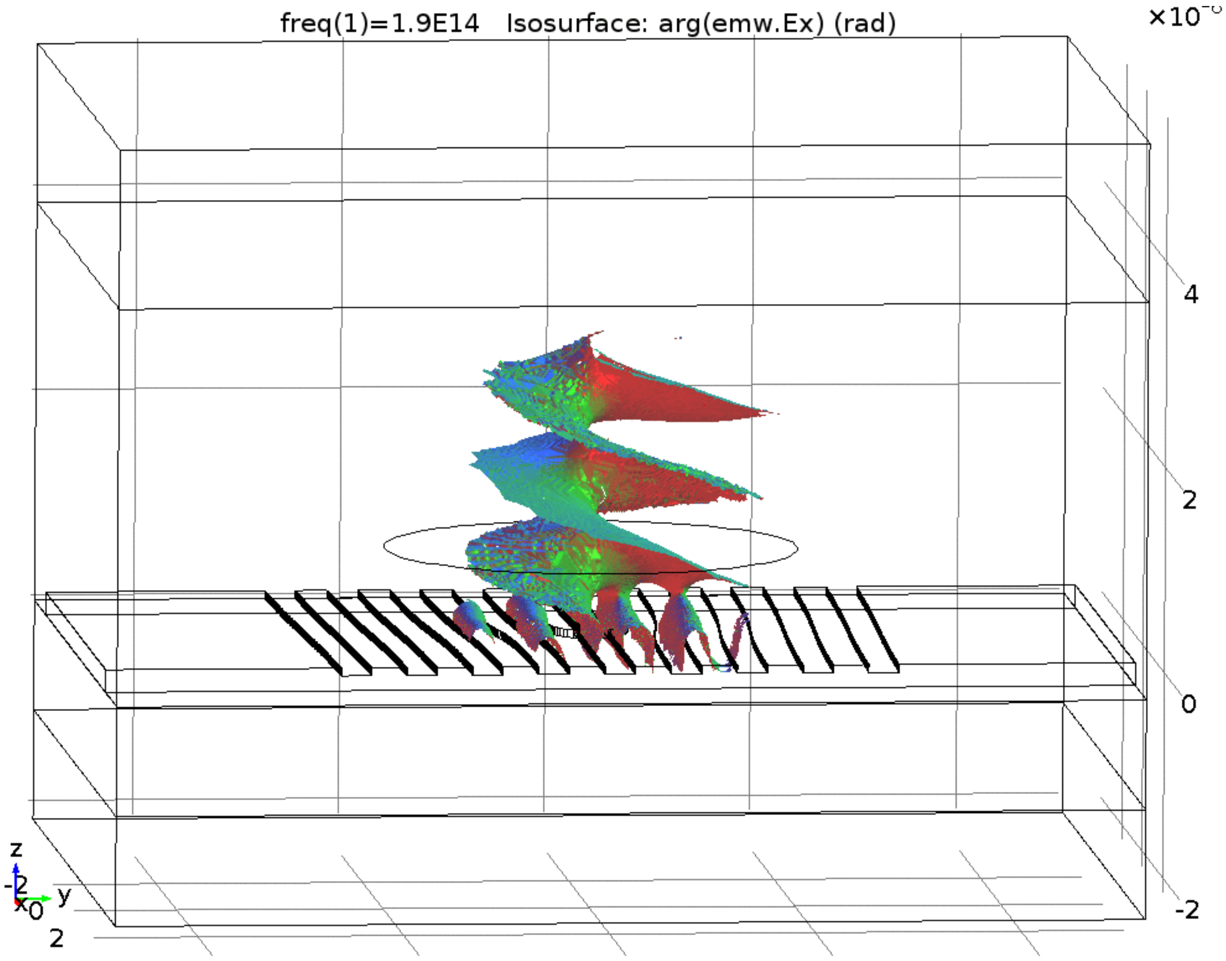
Helical phase of emerging vortex beam plainly evident in simulation

3D Modelling Innovations

Modeling of the FGC **requires full three dimensional models** as OAM fields are fundamentally 3D in nature.

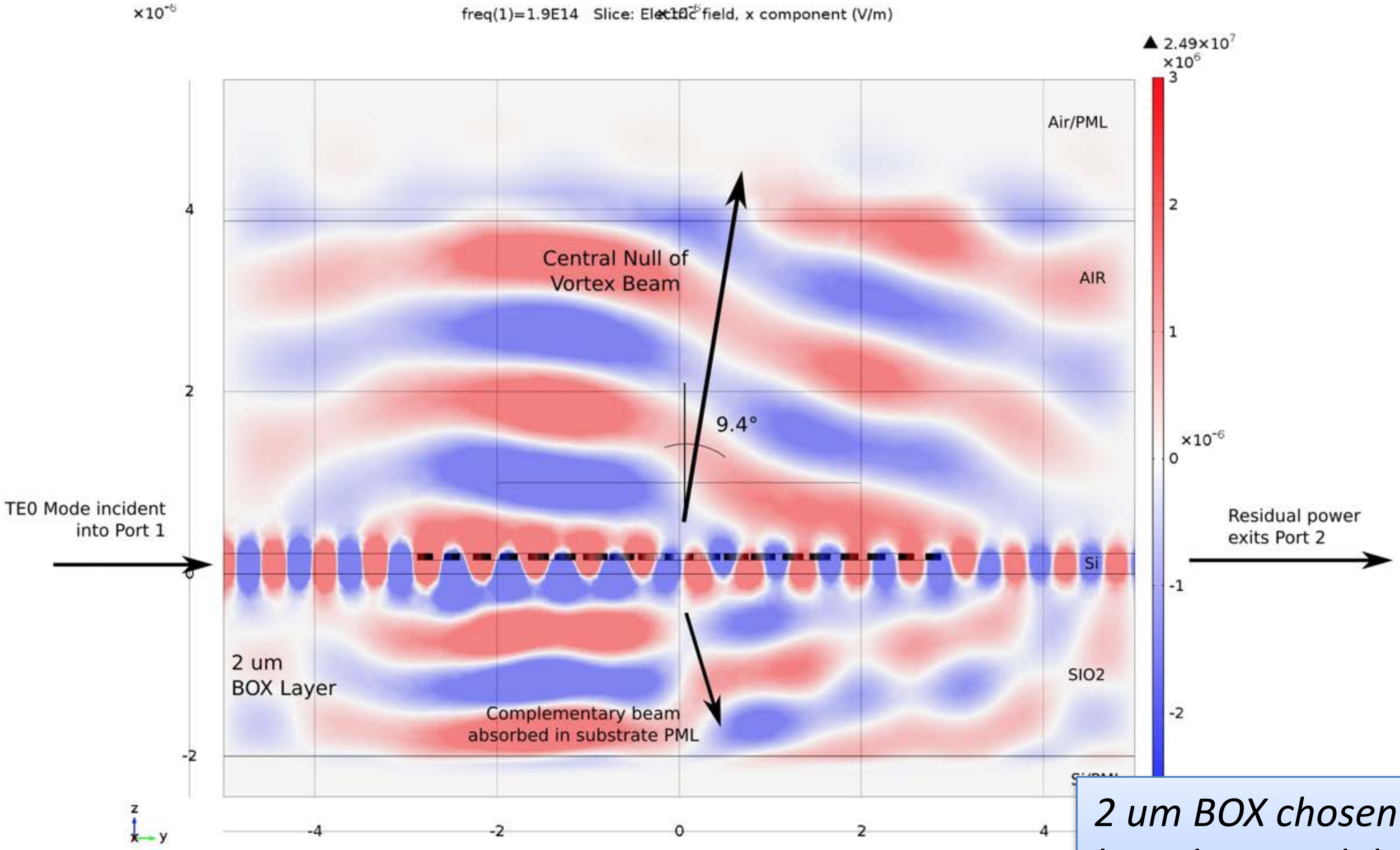
CPU and Memory Intense

Conventional (non-forked) grating coupler modelling **has been exclusively 2D.**



Phase=0 Iso-Surface

Simulation with 2um BOX



TE0 Mode incident into Port 1

Central Null of Vortex Beam

9.4°

Residual power exits Port 2

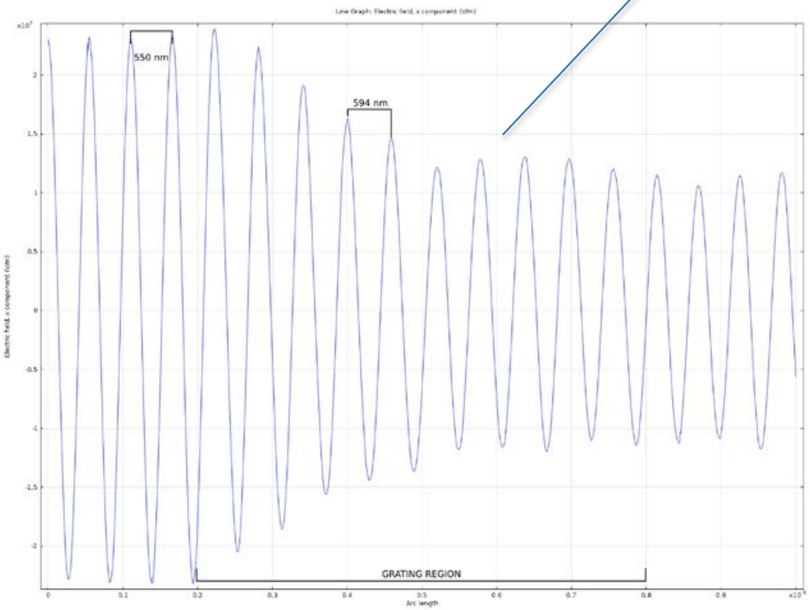
2 um BOX Layer

Complementary beam absorbed in substrate PML

2 um BOX chosen based on availability of stock SOI wafers

Propagation under Grating

It’s critical to predict α and β through the grating region.



The desgin value was 589 nm, but the observed value was 594 nm; this resulted in a beam pointing angle offset error.

1. Find α and β over range of design parameters using 2D parametric study.
2. Verified in final 3D model

Power Conservation and the Overlap Integral

P_{IN}	Incident Port 1 Power	1.0 W
P_{REF}	Reflected Power (Port 1)	0.026W
P_{TX}	Transmitted Power (Port 2)	0.178 W
P_{UP}	Total Upward Beam Power	0.435 W
P_{DN}	Total Downward Substrate Power	0.347 W
$P_{OUT} = P_{REF}+P_{TX}+P_{UP}\ P_{DN}$	Total Scattered Power	0.984 W
$P_{IN} - P_{OUT}$	“Lost” Power	0.016 W

$$c = \frac{\int \vec{E} \times \vec{H}_m^* \cdot \hat{z}\, dA}{\int \vec{E}_m \times \vec{H}_m^* \cdot \hat{z}\, dA}$$

$$\eta = \frac{\left|\int E\, E_m^*\, dA\right|^2}{\int |E|^2 dA \int |E_m|^2 dA}$$

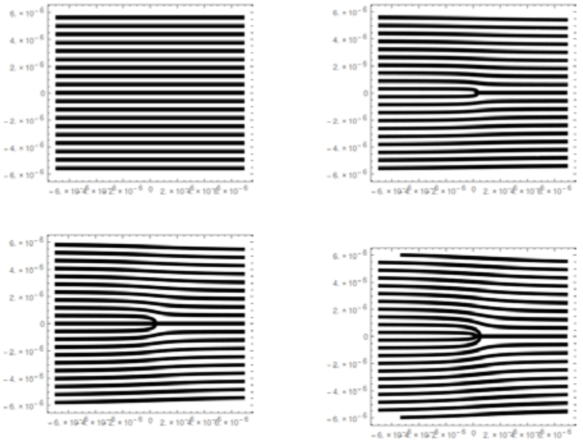
Evaluated Integral against Bessel Gaussian Mode “best” matched to grating size.

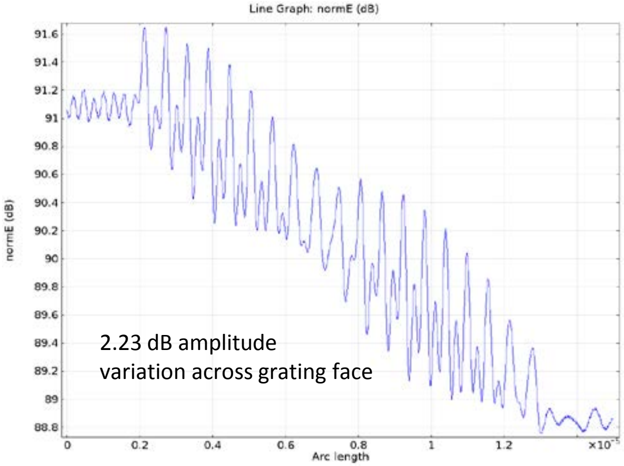
X=+2	χ=+1	χ=0	X=-1	X=-2
2.7%	3.7%	8.5%	78%	1.0%

12x12 um Grating Design

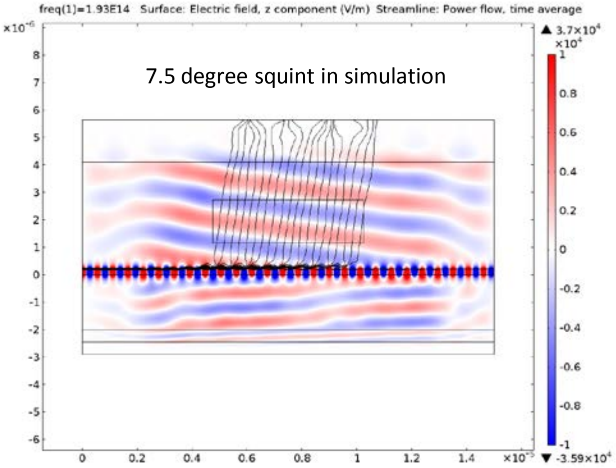
Currently in Fabrication

- 19 slots
- 25 nm slot depth – shallow slots hurt efficiency but helps amplitude balance.
- 281 nm slot width
- 593 nm avg pitch
- 8 degree squint design
- Charges 0, 1, 2, and 3





2.23 dB amplitude variation across grating face



7.5 degree squint in simulation

Conclusions and Summary

- The Forked Grating Coupler (FGC) can dramatically reduce the size, cost, and complexity of optical vortex interfaces on photonic ICs.
- The use of 3D modeling is essential for synthesizing, verifying, and optimizing the design of this structure.

Clarkson
UNIVERSITY

CUNY
The City
University
of
New York

NSF

CfM
Center for
Metamaterials

The Forked Grating Coupler work is supported by the NSF Center for Metamaterials I/UCRC and Corning Incorporated.

ACKNOWLEDGEMENTS