UNIVERSITÀ DEGLI STUDI DI PADOVA

laboratory for nanofabrication of nanodevices

Istituto Officina dei Materiali

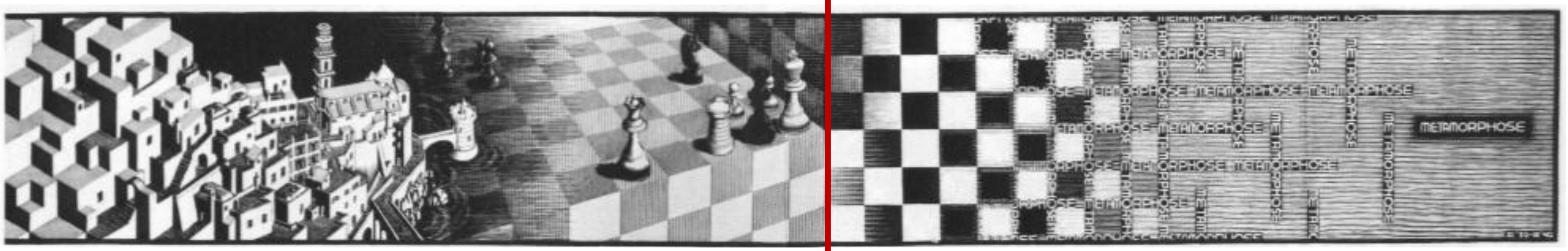
Development of new (nano) optics¶ METAMORPHOSIS OF NANOSTRUCTURED LENSES: HYBRIDIZATION AND FREE-FORM METALENSES FOR TOTAL ANGULAR MOMENTUM CONTROL

Filippo Romanato[1,2,3]

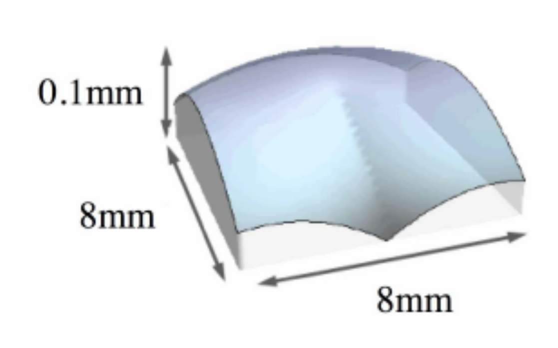
Gianluca Ruffato[1,2], P. Capaldo[2,3]

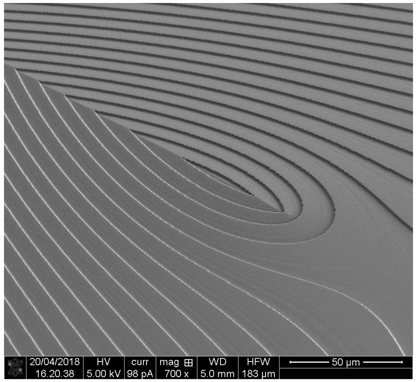
[1] Department of Physics and Astronomy "G. Galilei", University of Padova, Padova, Italy

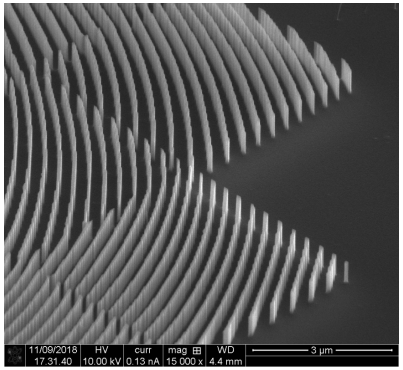
Optics change the word, lenses change the optics



3D	3D-2D	2D





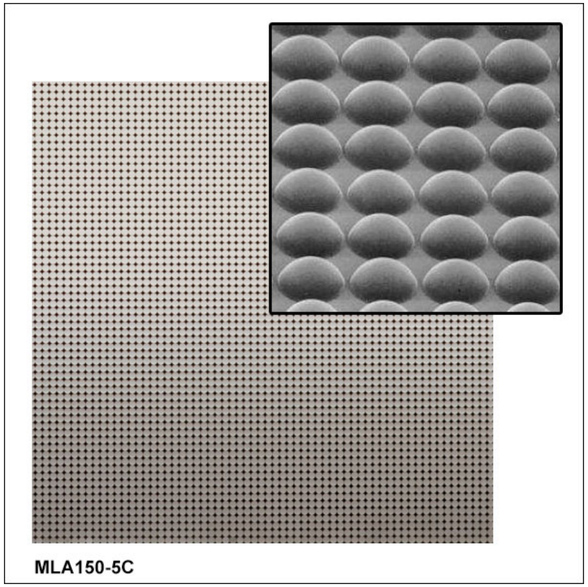


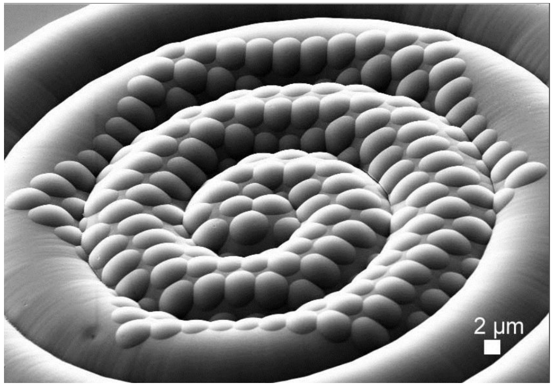
refractive lenses
Bulky, Large
Single function

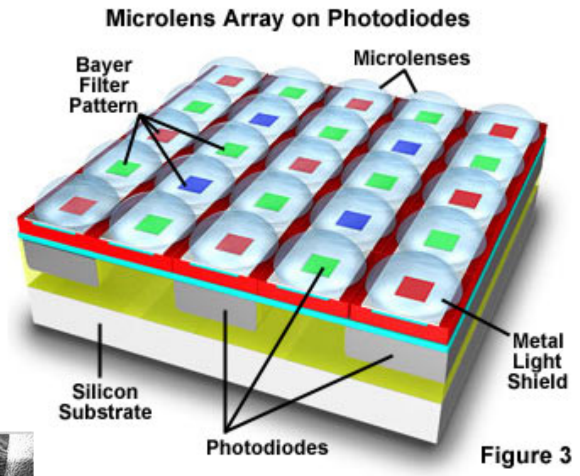
Kinoform lenses
Almost flat
Multi function

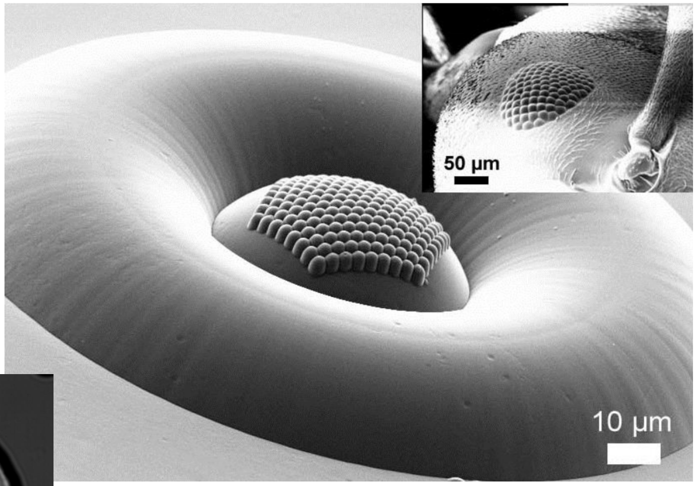
Metalenses
Flat
Multi function
Polarization

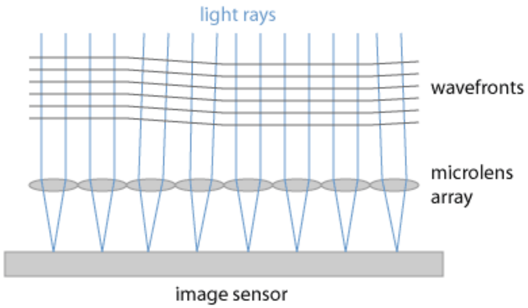
Microlenses

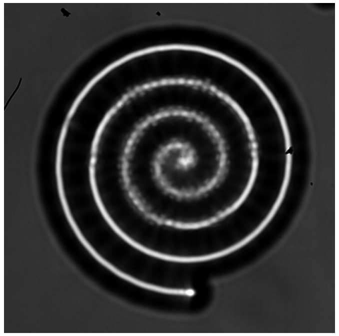


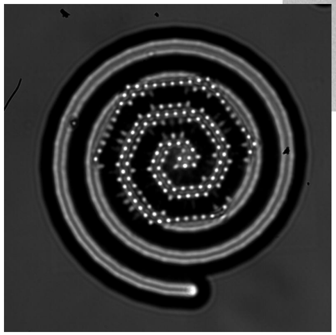


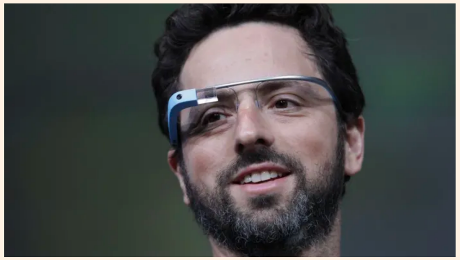








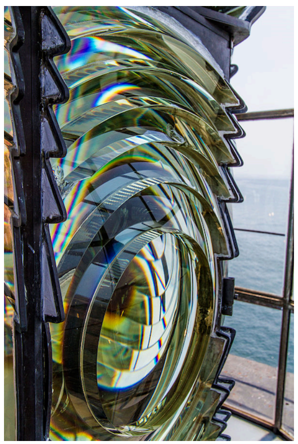


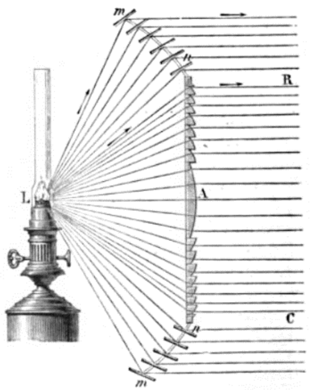

Google unveils prototype ‘smart’ glasses

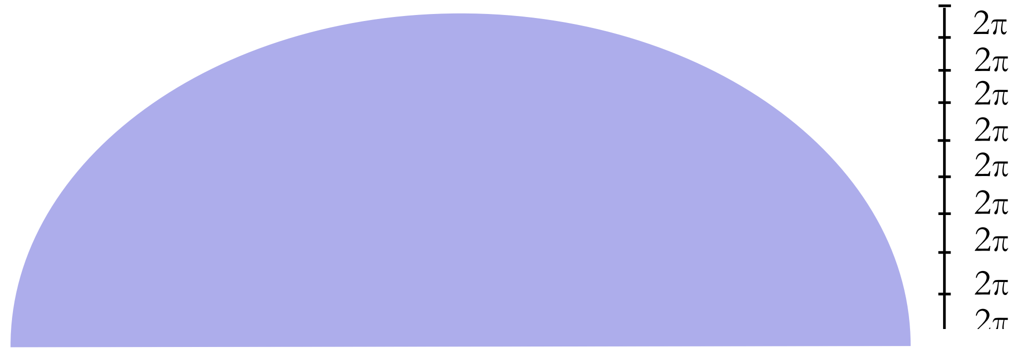
Google co-founder Sergey Brin shows off Google Glass at an event in San Francisco © AP

Diffractive optical elements

The concept of diffractive optics was firstly implemented by A. Fresnel in 1827 and applied to a novel design of lighthouses.





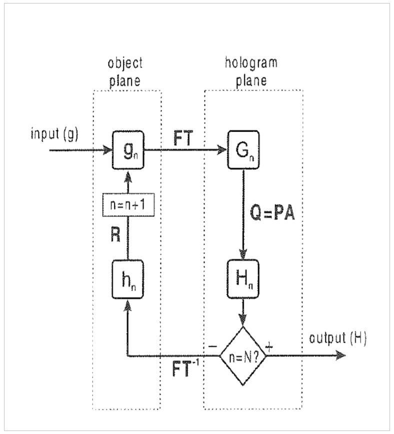


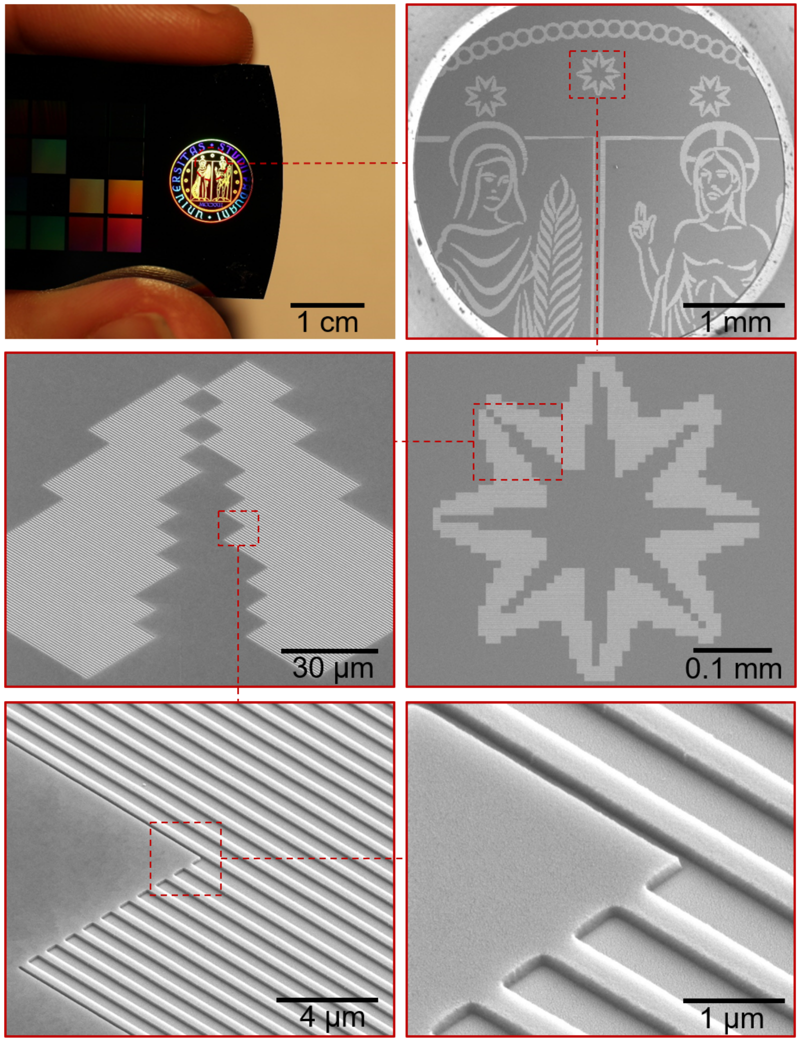
$$d = \frac{\lambda}{n-1}$$

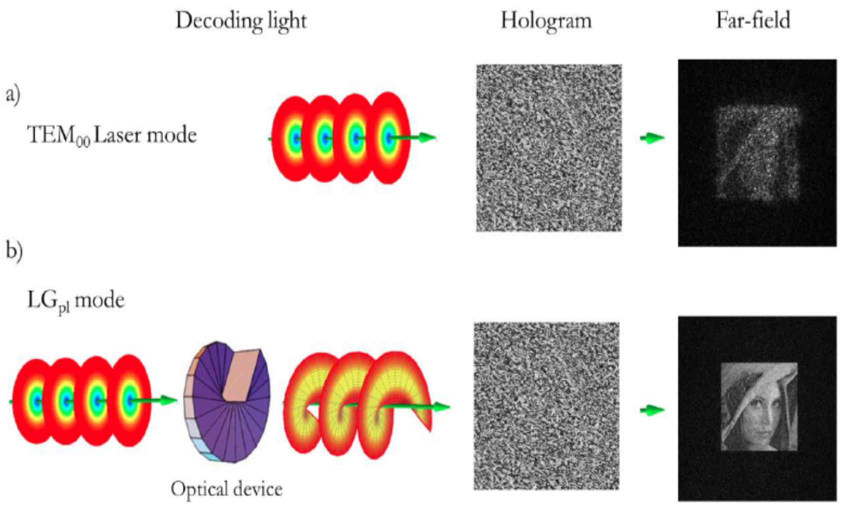
λ=632.8 nm (laser HeNe)
n~1.5 (glass)

d~1265 nm

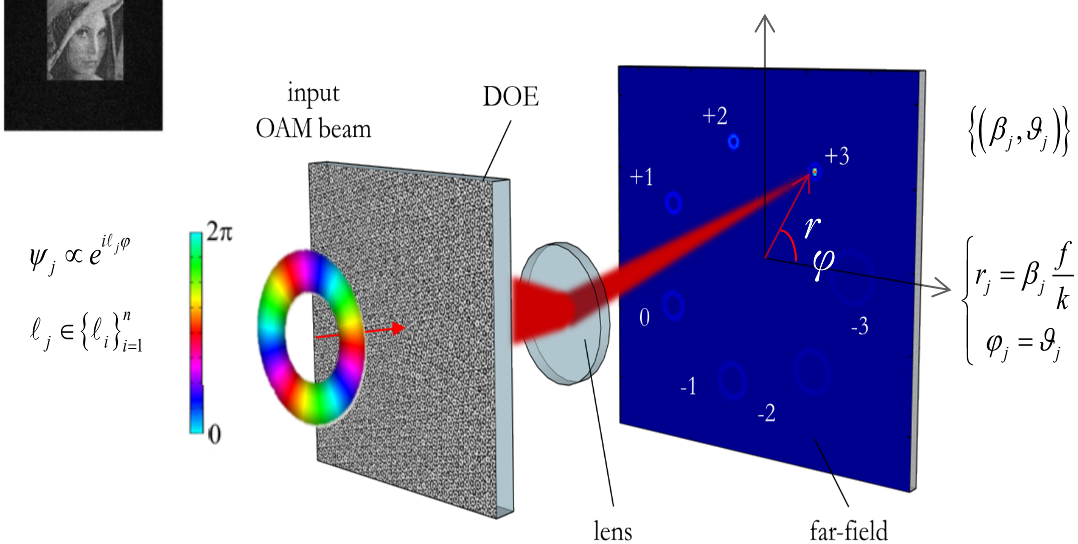
Iterative Fourier Transform Algorithm (IFTA) with Error-Reduction Approach (Gerchberg and Saxton algorithm)







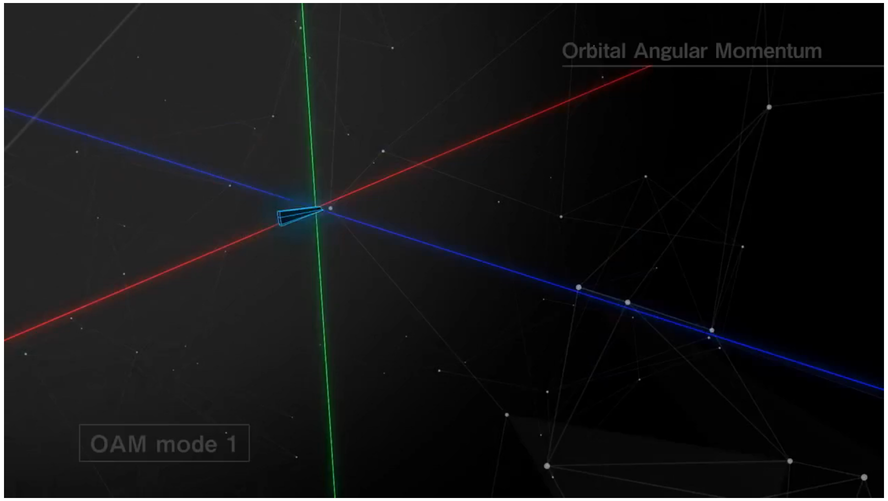
Diffractive optics for modal decomposition into a harmonic set: OAM-mode analyzer

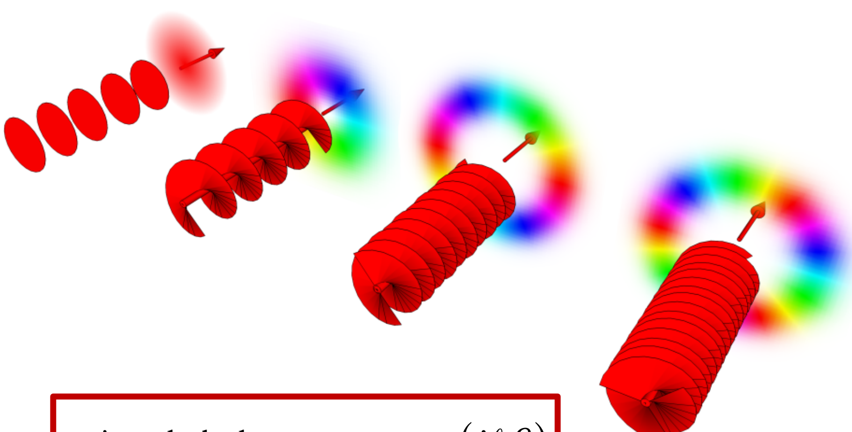


$$\Omega_{DOE}(\rho,\vartheta) = \arg\left\{\sum_{j=1}^{n} c_j \psi_j^* \exp\left[i\rho\beta_j\cos\left(\vartheta-\vartheta_j\right)\right]\right\}$$

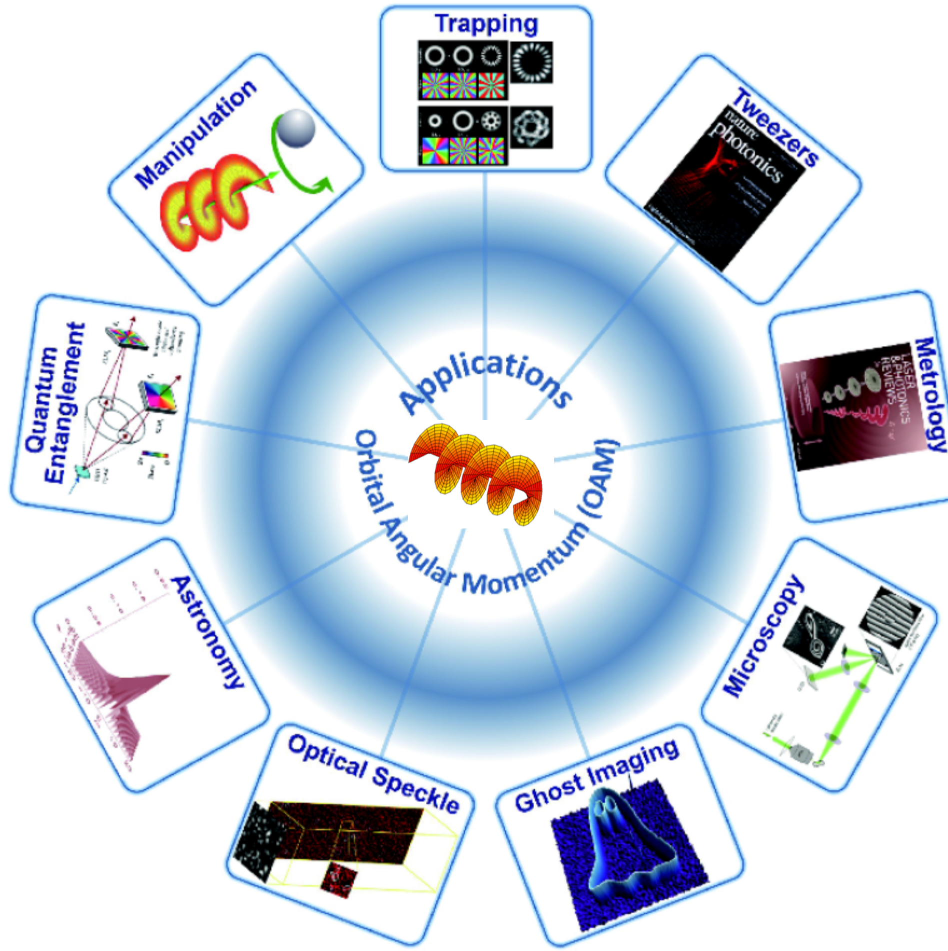
Ruffato G., Massari M. and Romanato F., *Sci. Rep.* **6**, 24760 (2016)

The orbital angular momentum (OAM) of light



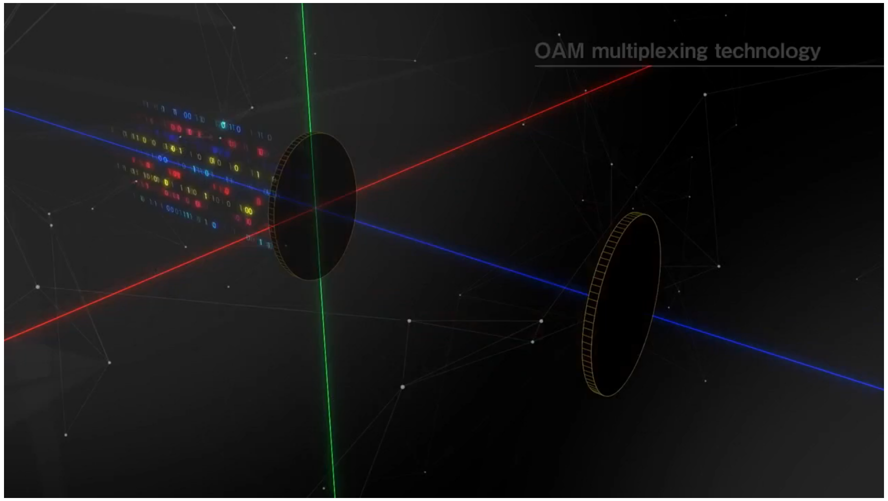


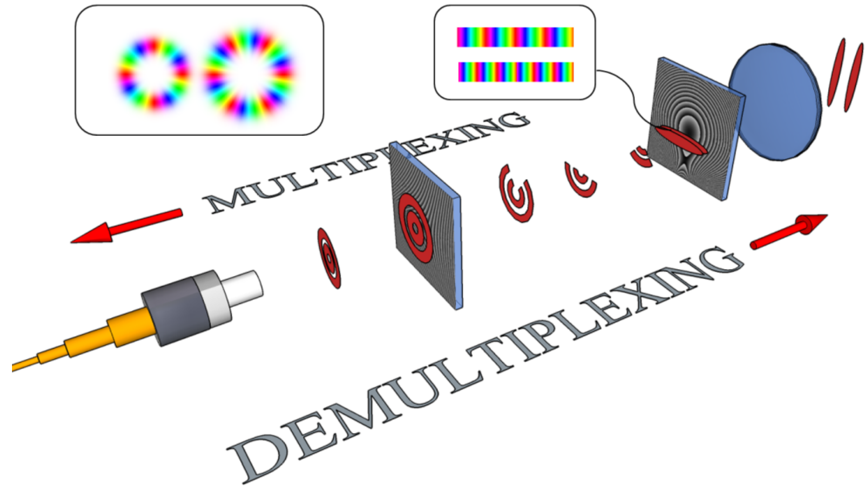
azimuthal phase: $\exp\left(i\ell\vartheta\right)$

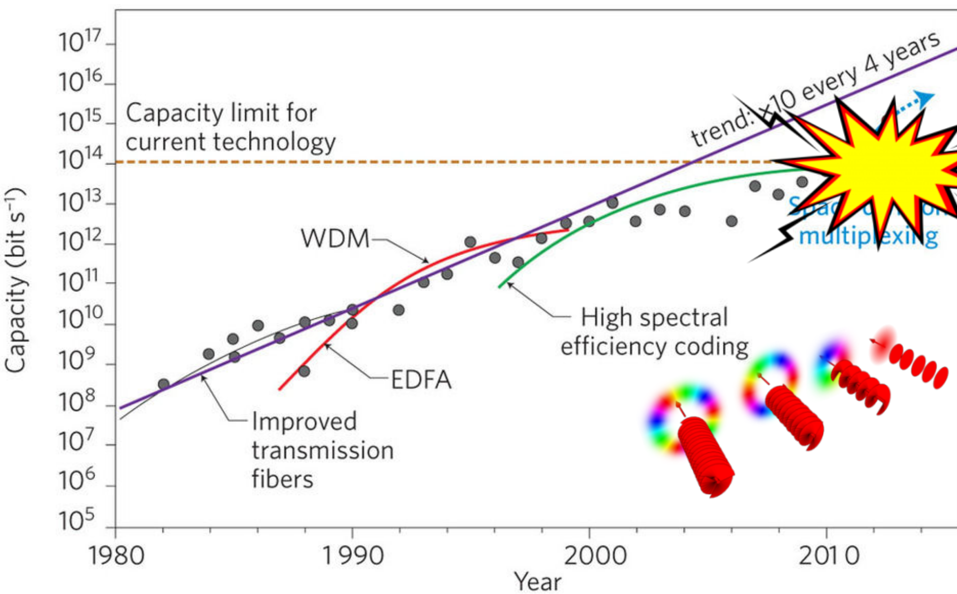


J. Wang, Science China: Physics, Mechanics and Astronomy, 62, 3, 034201 (2019).

OAM for information encoding (SDM/MDM)







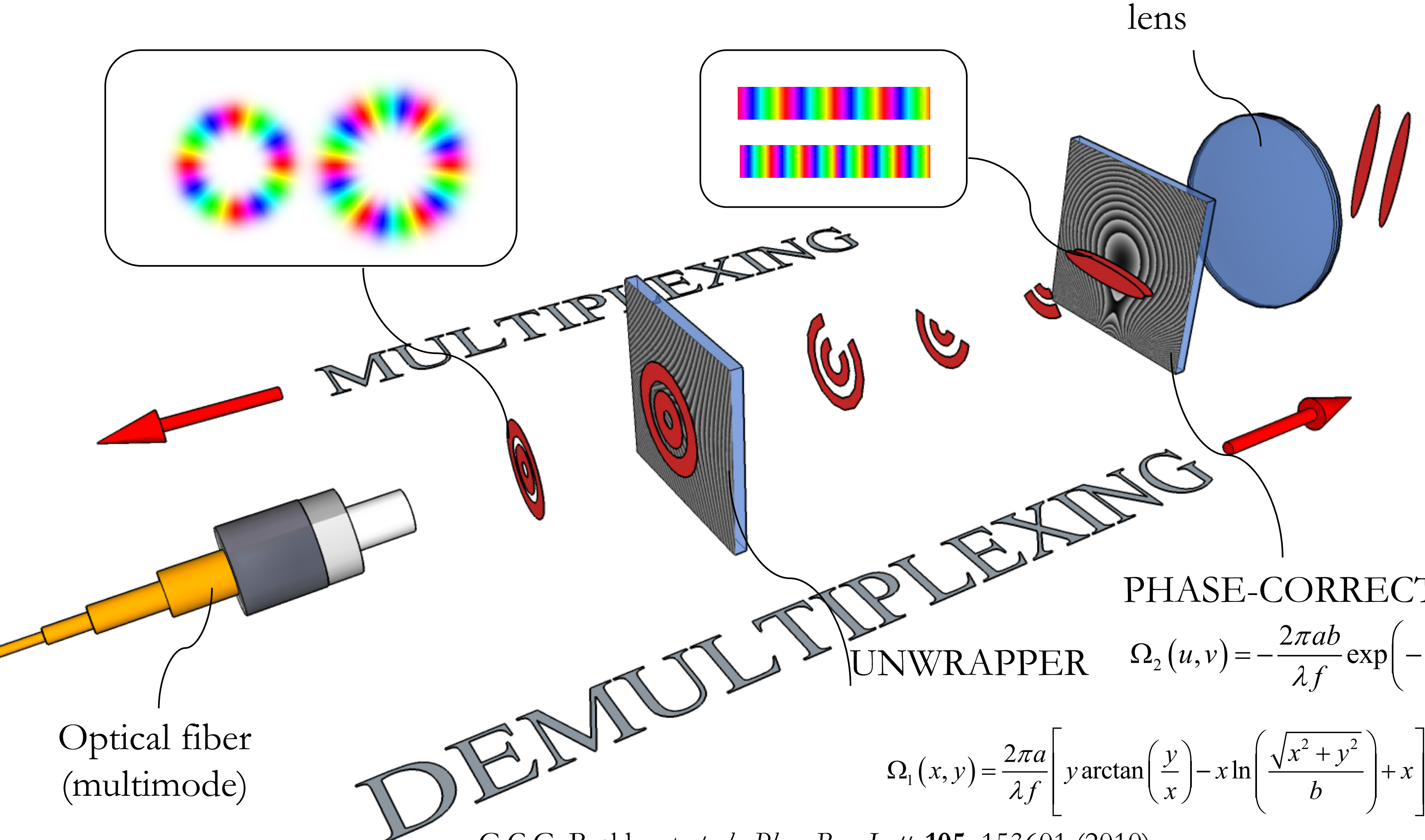
D. J. Richardson, J.M. Fini, and L.E. Nelson, Nat. Photon. 7, 354-362 (2013)

In the last decade, important steps forward the generation and sorting of OAM beams in an efficient and compact way (e.g. log-pol sorter)

However, optical devices are still missing for:
- OAM multiplication
- OAM division
- Routing
- Switching

Is there a solution to manipulate OAM in an efficient and compact way?

log-pol optical transformation

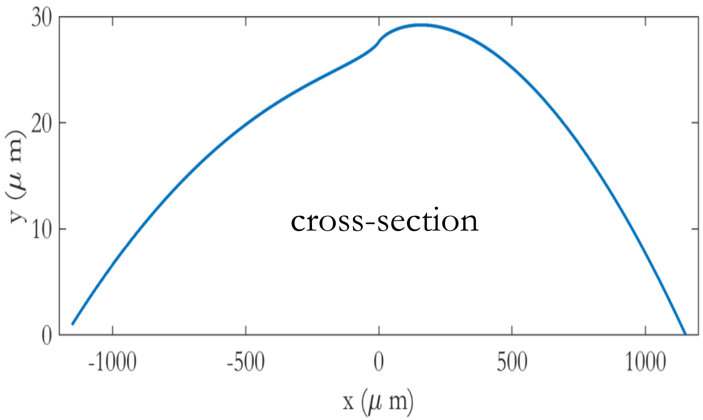


$$\Omega_2(u,v) = -\frac{2\pi ab}{\lambda f}\exp\left(-\frac{u}{a}\right)\cos\left(\frac{v}{a}\right)$$

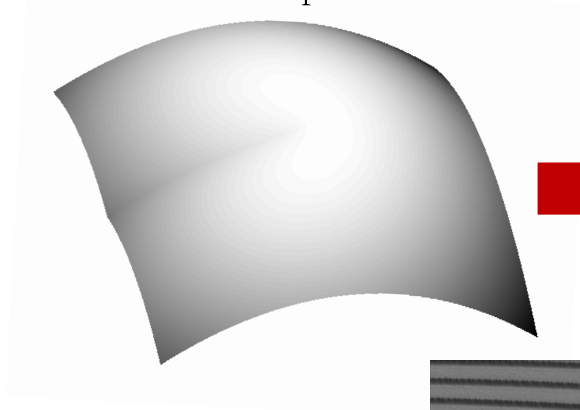
$$\Omega_1(x,y) = \frac{2\pi a}{\lambda f}\left[y\arctan\left(\frac{y}{x}\right) - x\ln\left(\frac{\sqrt{x^2+y^2}}{b}\right) + x\right] - k\frac{r^2}{2f}$$

G.C.G. Berkhout *et al.*, *Phys. Rev. Lett.* **105**, 153601 (2010)
M. P. J. Lavery, et al., Opt. Express 20, 2110-2115 (2012)
Ruffato, G.,et al. & Romanato , Sci. Rep. 8, 10248 (2018).

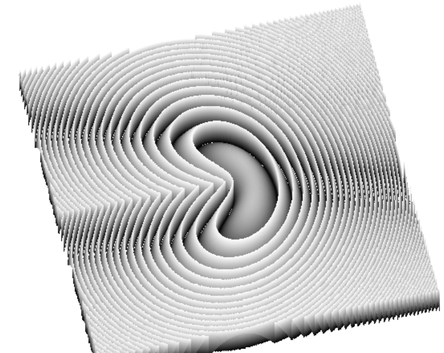
Diffractive optics approach (since 2017)

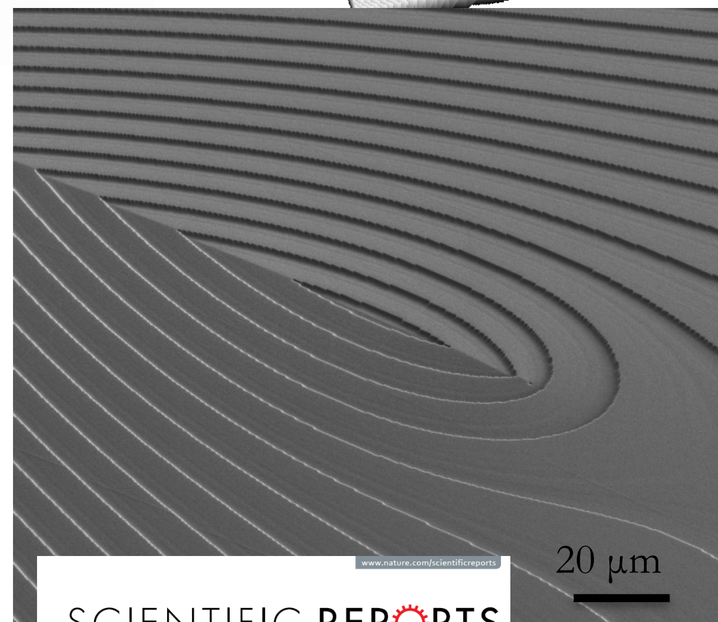


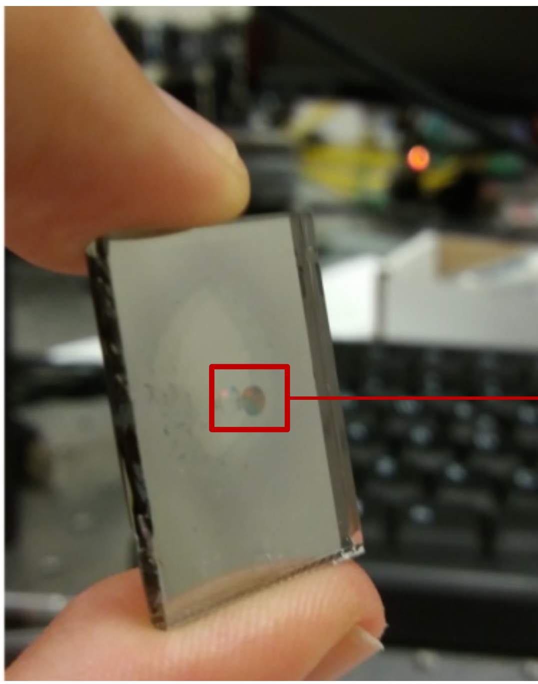
refrative optics



diffractive optics



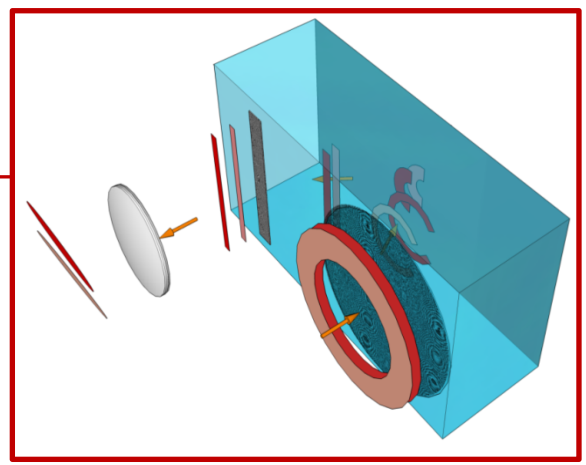




MINIATURIZATION

COMPACTNESS

EFFICIENCY



www.nature.com/scientificreports

SCIENTIFIC REPORTS

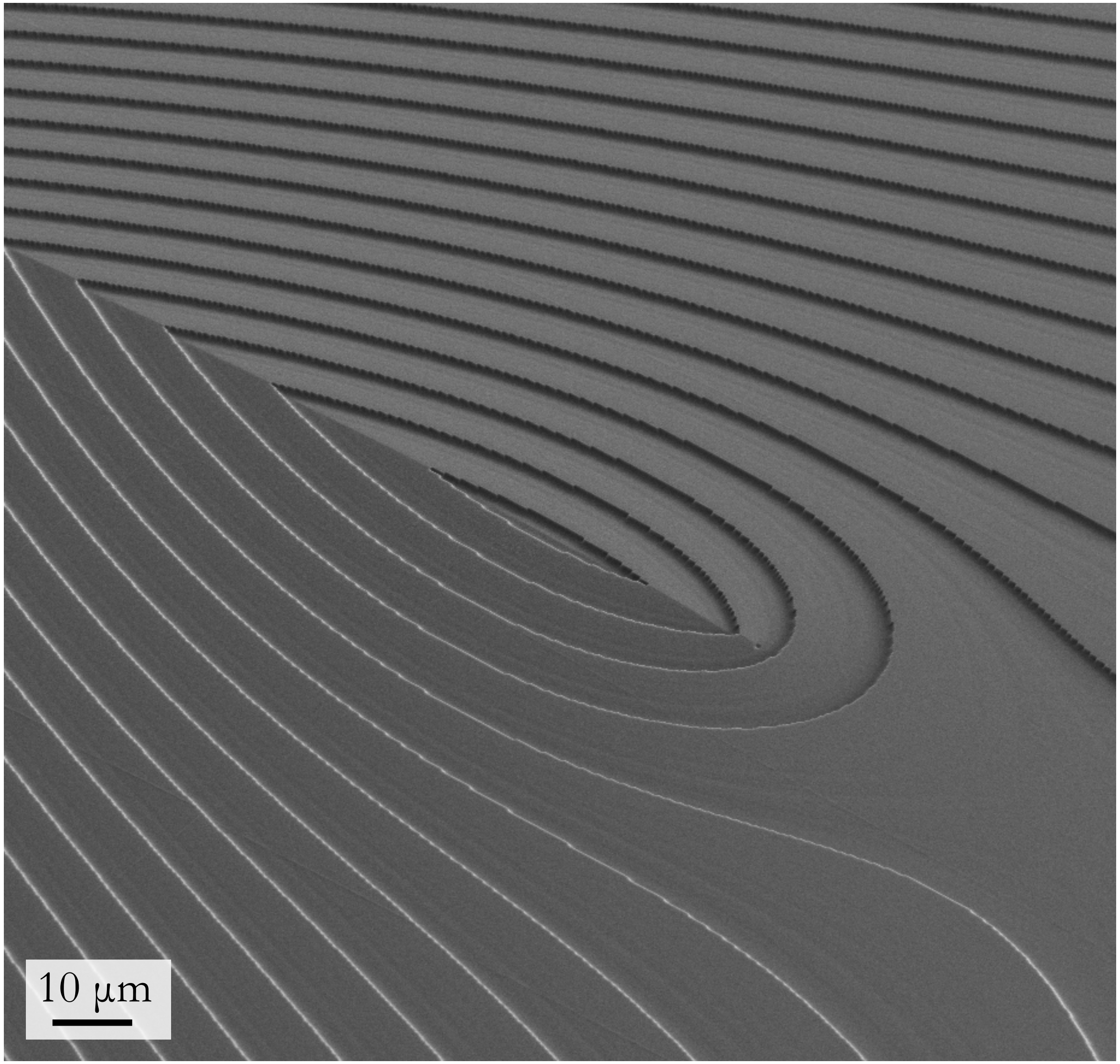
OPEN

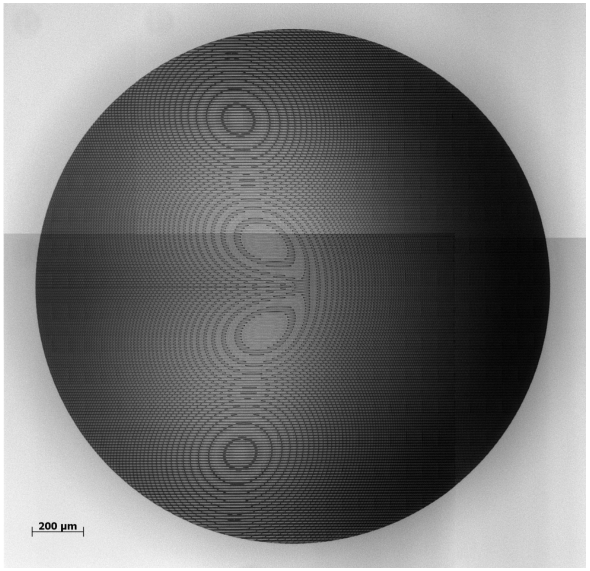
A compact diffractive sorter for high-resolution demultiplexing of orbital angular momentum beams

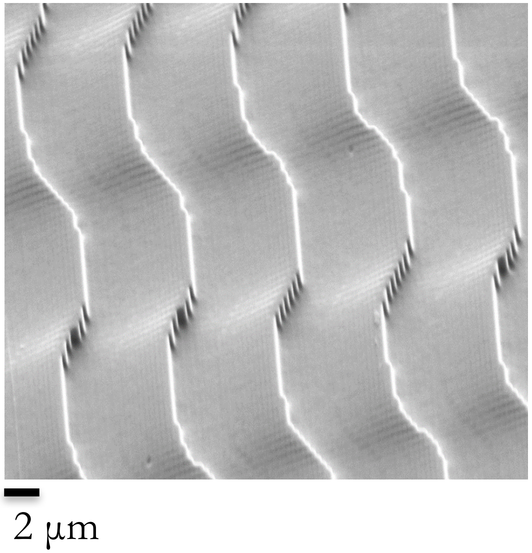
Received: 1 March 2018
Accepted: 25 June 2018
Published online: 06 July 2018

Gianluca Ruffato[1,2], Marcello Girardi[1,2], Michele Massari[1,2], Erfan Mafakheri[1,2], Bereneice Sephton[3], Pietro Capaldo[2,4], Andrew Forbes[3] & Filippo Romanato[1,2,4]

SEM inspection: unwrapper

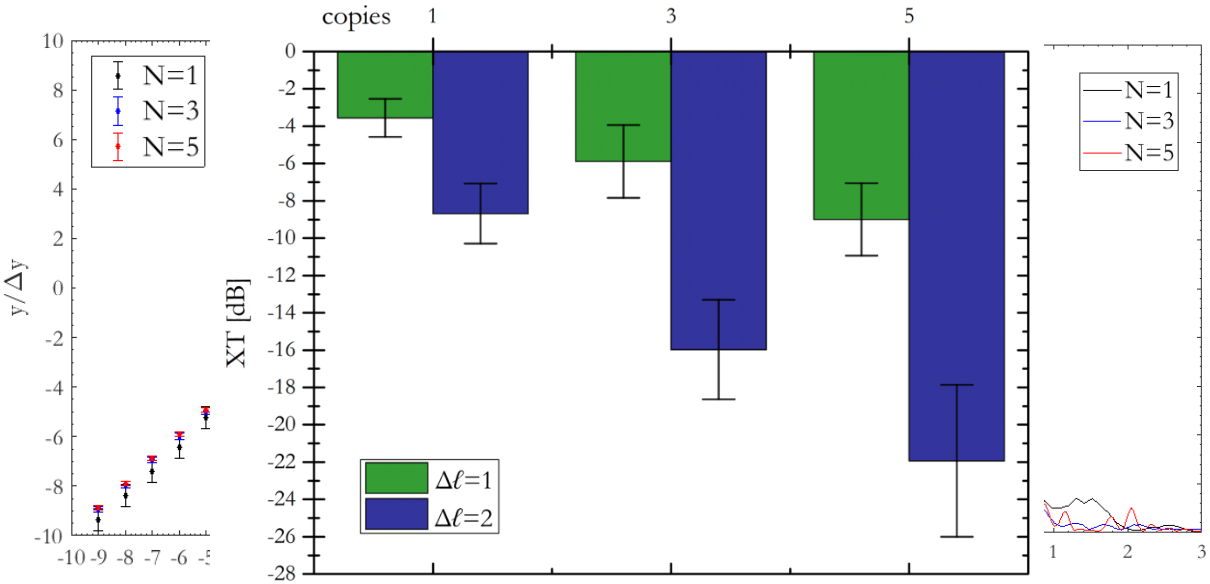


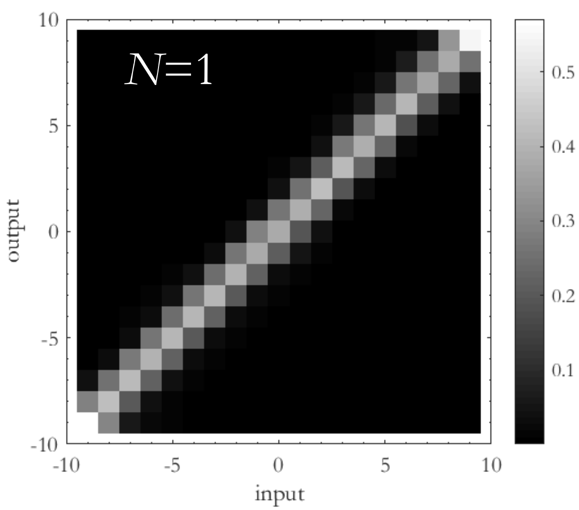




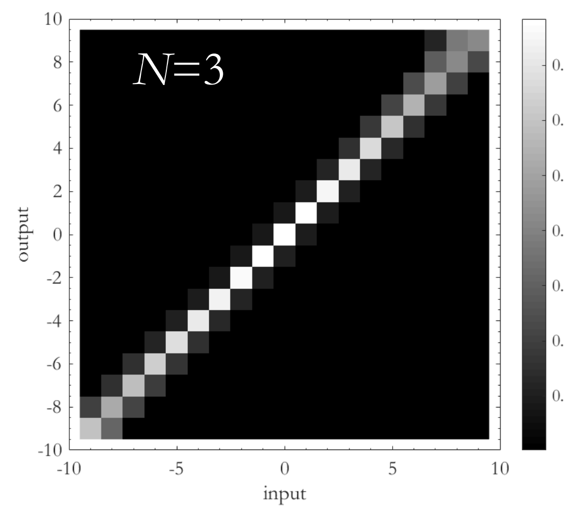
Optical characterization: cross-talk

Università degli Studi di Padova

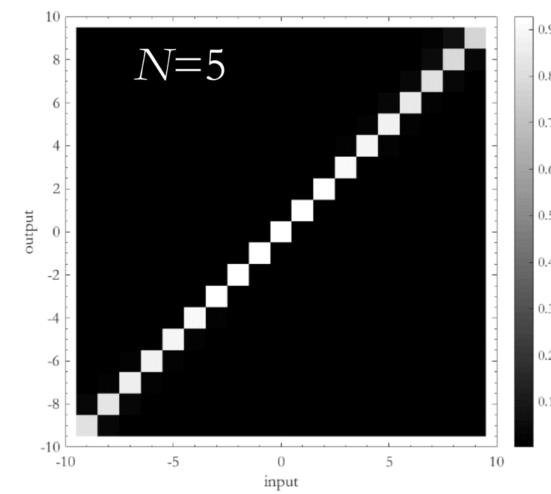




XT(Δℓ=1)=-2.32 dB
XT(Δℓ=2)=-8.45 dB



XT(Δℓ=1)=-5.79 dB
XT(Δℓ=2)=-16.01 dB



XT(Δℓ=1)=-9.13 dB
XT(Δℓ=2)=-21.9 dB

Research outputs on multiplexing (2017-19)

Research Article | Vol. 25, No. 7 | 3 Apr 2017 | OPTICS EXPRESS 7859
Optics EXPRESS

Test of mode-division multiplexing and demultiplexing in free-space with diffractive transformation optics

Gianluca Ruffato,[1,2,*] Michele Massari,[1,2] Giuseppe Parisi,[3] and Filippo Romanato[1,2,4]

[1]Department of Physics and Astronomy 'G. Galilei', University of Padova, via Marzolo 8, 35131 Padova, Italy
[2]Laboratory for Nanofabrication of Nanodevices, c.so Stati Uniti 4, 35127 Padova, Italy
[3]SM Optics – SIAE Group, Via M. Buonarroti 21, 20093 Cologno Monzese, Milano, Italy
[4]CNR -INFM TASC IOM National Laboratory, S.S. 14 Km 163.5, 34012 Basovizza, Trieste, Italy
*gianluca.ruffato@unipd.it

Research Article | Vol. 27, No. 17 / 19 August 2019 / *Optics Express* 24123
Optics EXPRESS

Non-paraxial design and fabrication of a compact OAM sorter in the telecom infrared

G. Ruffato,[1,2] M. Massari,[2,3] M. Girardi,[1,2] G. Parisi,[4] M. Zontini,[4] and F. Romanato[1,2,3,4,*]

[1]Department of Physics and Astronomy 'G. Galilei', University of Padova, via Marzolo 8, 35131 Padova, Italy
[2]LANN, Laboratory for Nanofabrication of Nanodevices, EcamRicert, Corso Stati Uniti 4, 35127 Padova, Italy
[3]CNR-INFM TASC IOM National Laboratory, S.S. 14 Km 163.5, 34149 Basovizza, Trieste, Italy
[4]SM Optics – SIAE Microelettronica Group, Via M. Buonarroti 21, 20093 Cologno Monzese, Milano, Italy

www.nature.com/scientificreports
SCIENTIFIC REPORTS
OPEN
Received: 11 January 2016
Accepted: 04 April 2016
Published: 20 April 2016

Diffractive optics for combined spatial- and mode- division demultiplexing of optical vortices: design, fabrication and optical characterization

Gianluca Ruffato[1,2], Michele Massari[1,2] & Filippo Romanato[1,2,3]

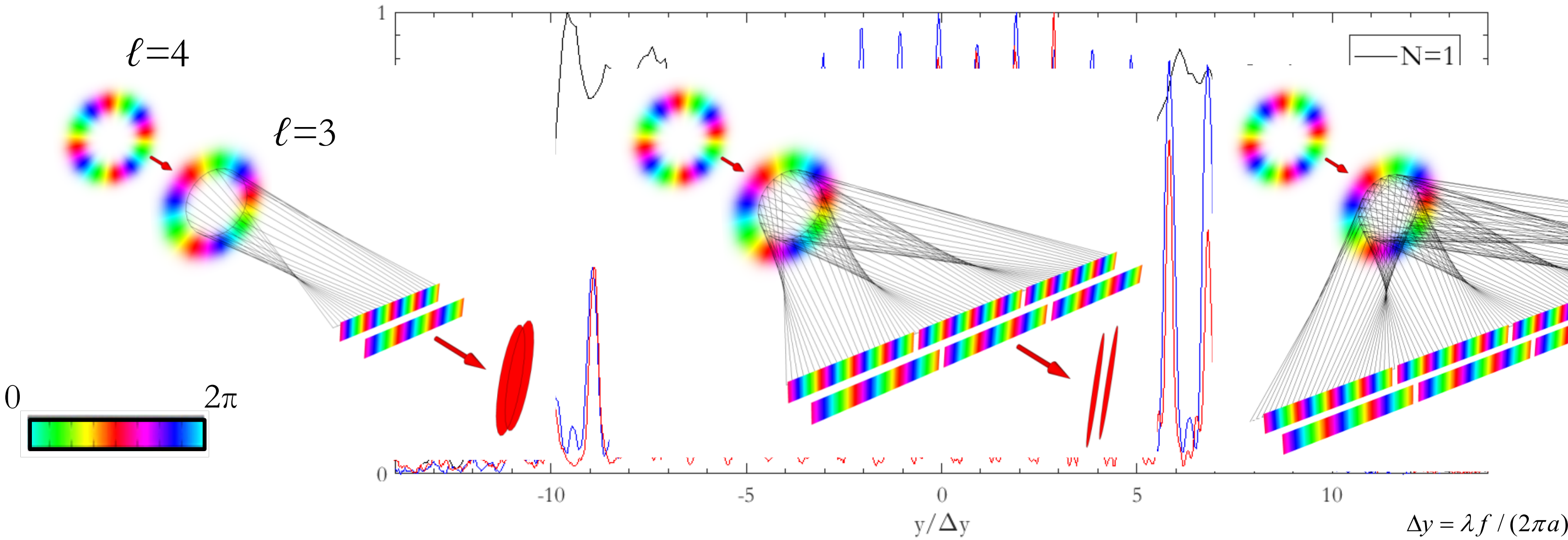
Letter | Vol. 42, No. 3 / February 1 2017 / *Optics Letters* 551
Optics Letters

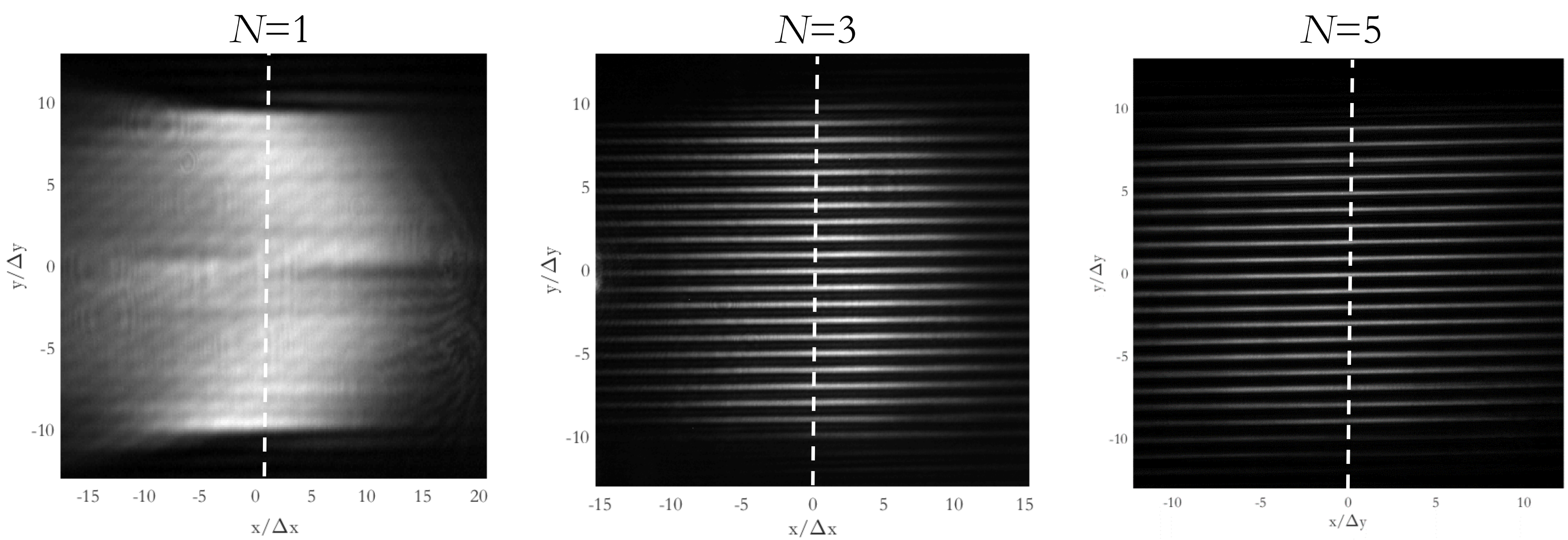
Compact sorting of optical vortices by means of diffractive transformation optics

Gianluca Ruffato,[1,2,*] Michele Massari,[1,2] and Filippo Romanato[1,2,3]

[1]Department of Physics and Astronomy "G. Galilei," University of Padova, via Marzolo 8, 35131 Padova, Italy
[2]Laboratory for Nanofabrication of Nanodevices, c.so Stati Uniti 4, 35127 Padova, Italy
[3]CNR-INFM TASC IOM National Laboratory, S. S. 14 Km 163.5, 34012 Basovizza, Trieste, Italy
*Corresponding author: gianluca.ruffato@unipd.it

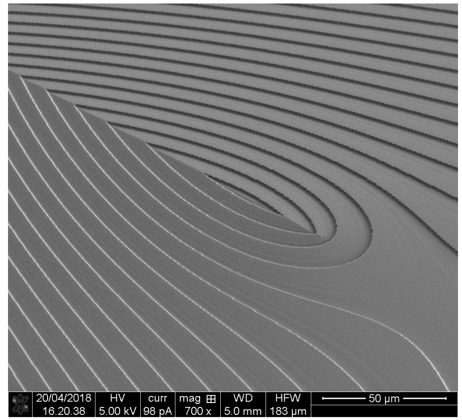
Optical characterization for $\ell=\{-9,\ldots,+9\}$

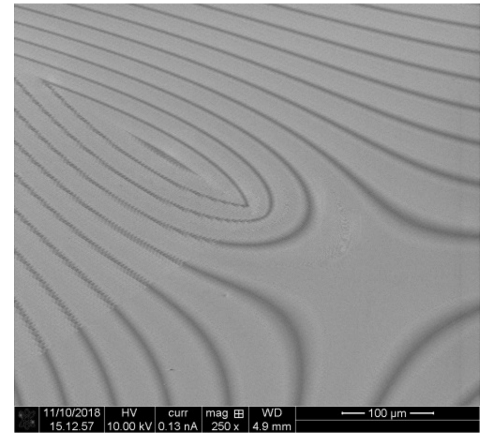




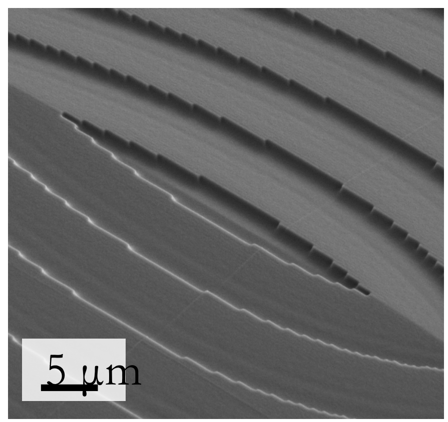
From diffractive optics to metasurfaces (2019)

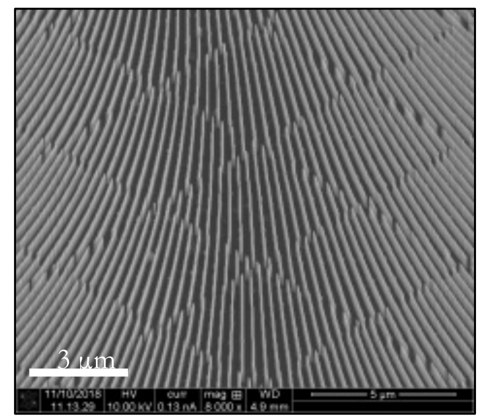
The same phase map





Different microscopic structure

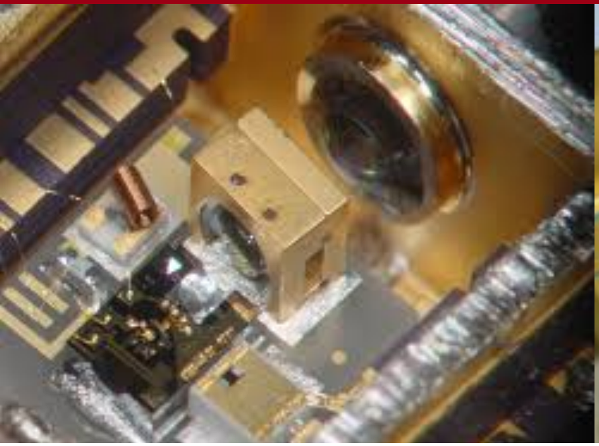


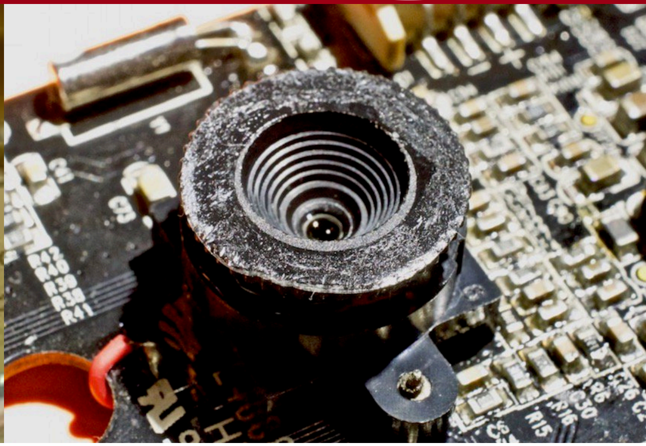


Ruffato, G. et al. & Romanato , Opt. Express 27(11), 15750-15764 (2019) c

Optics & electronics: the size/material divide

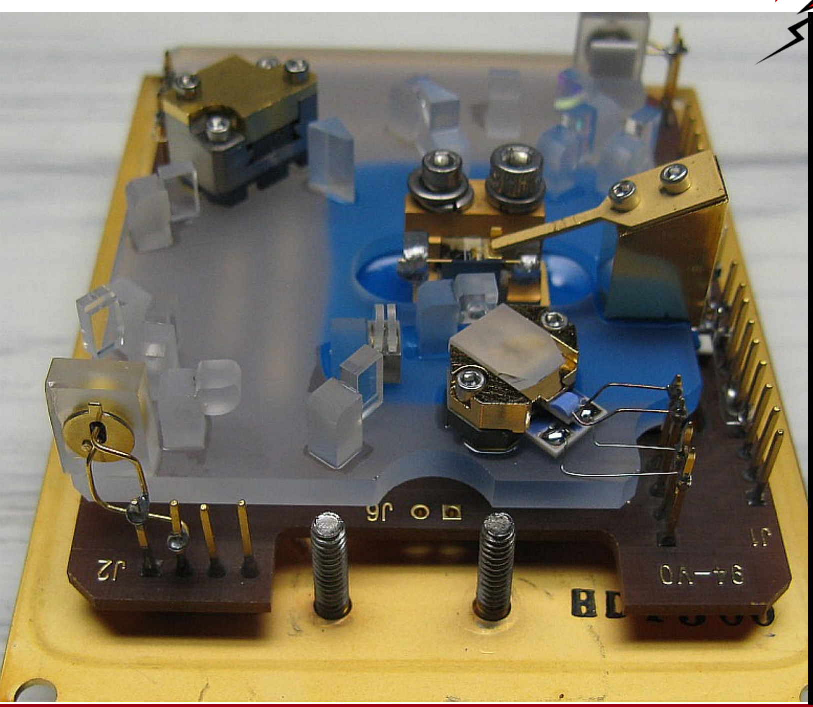
Università degli Studi di Padova

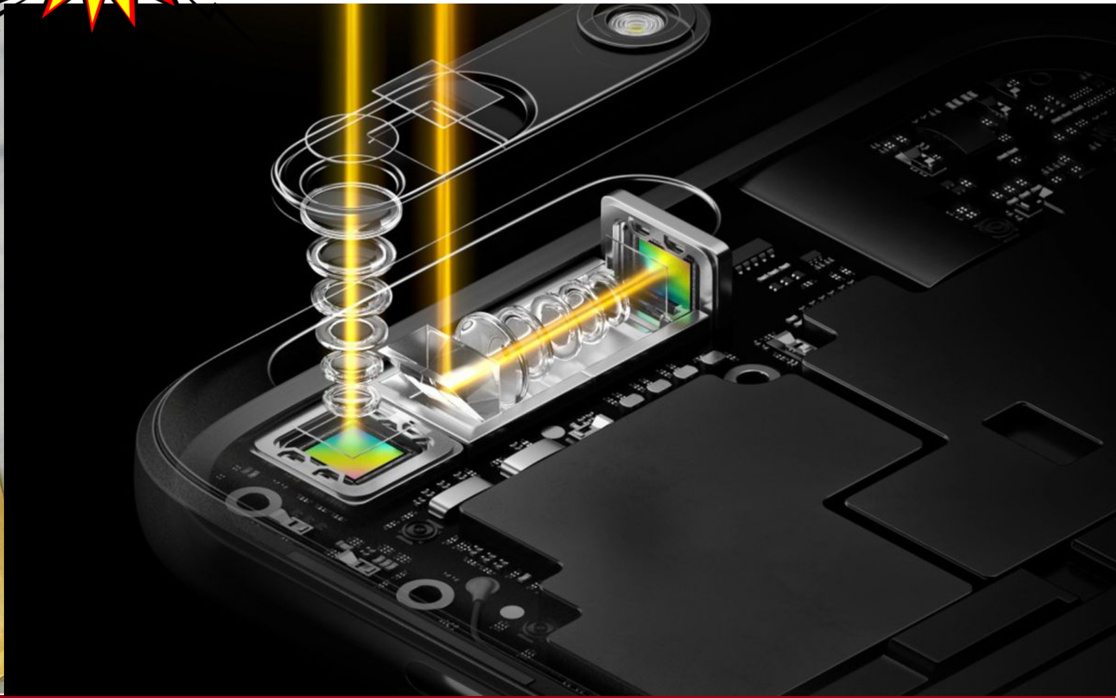




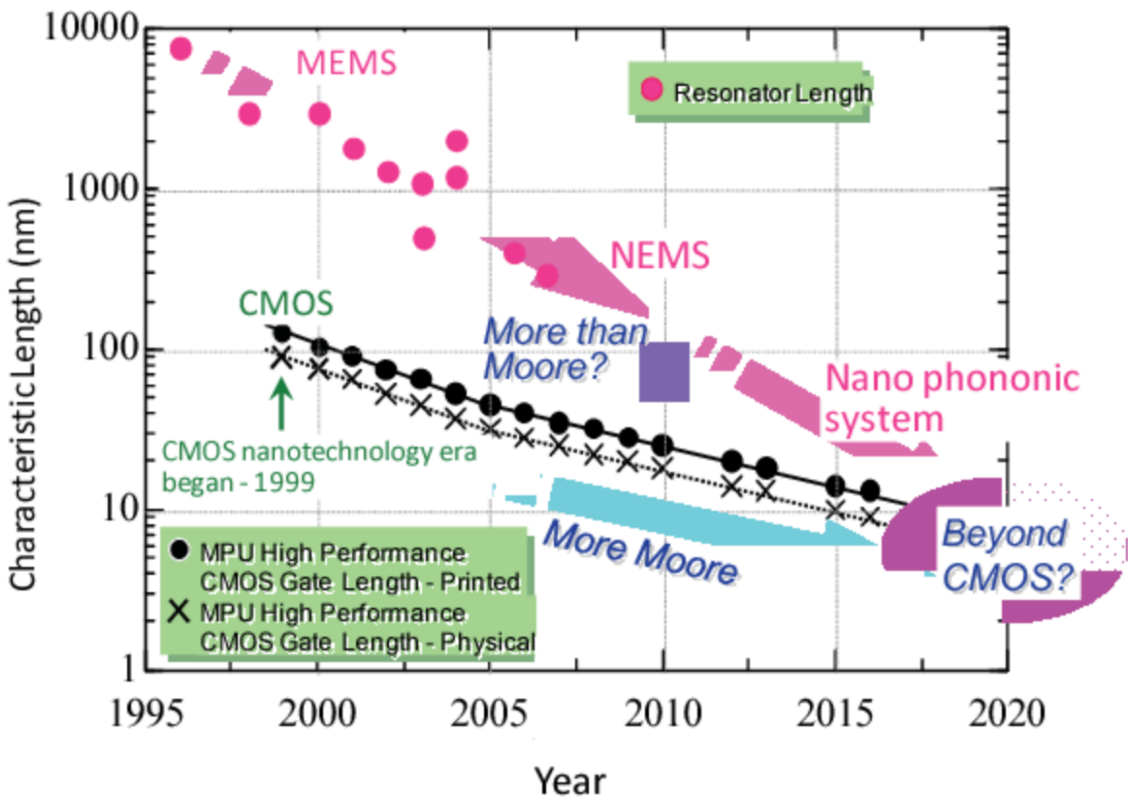
Miniaturized glass optics

Integrated Silicon electronics





The



g. 1 Recent trend of MEMS/NEMS downscaling along with CMC

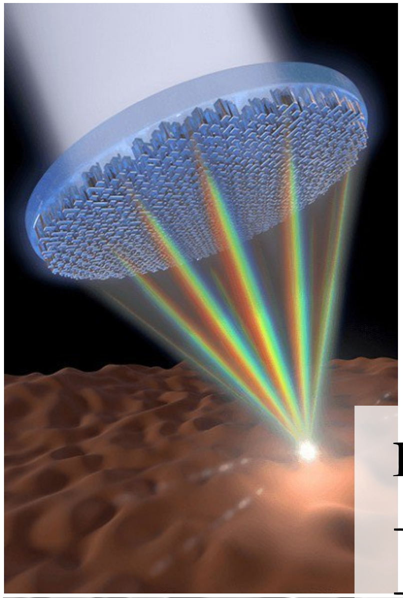
Fig. 1 Recent trend of MEMS/NEMS downscaling along with CMOS miniaturization.

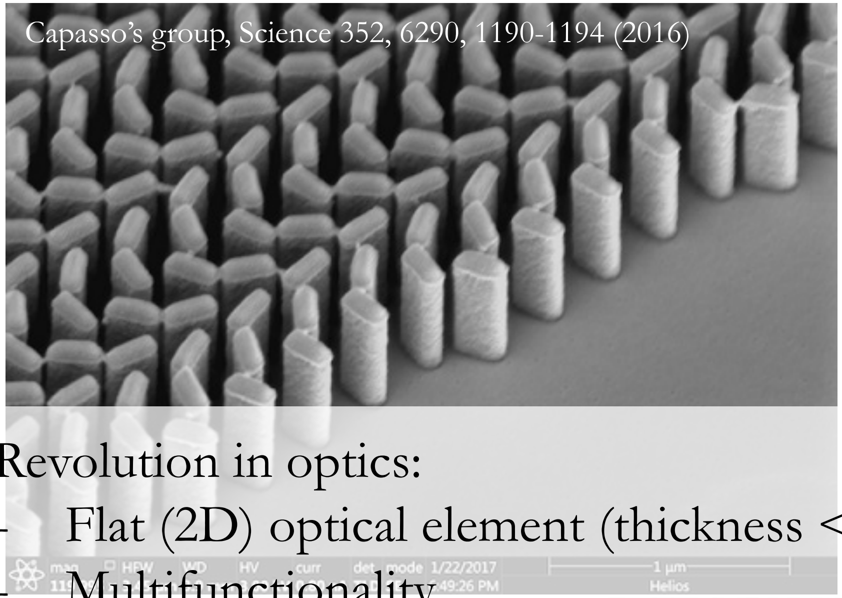
Published in 2011 IEEE International Conference on IC Design & Technology 2011

Scaled nanoelectromechanical (NEM) hybrid devices

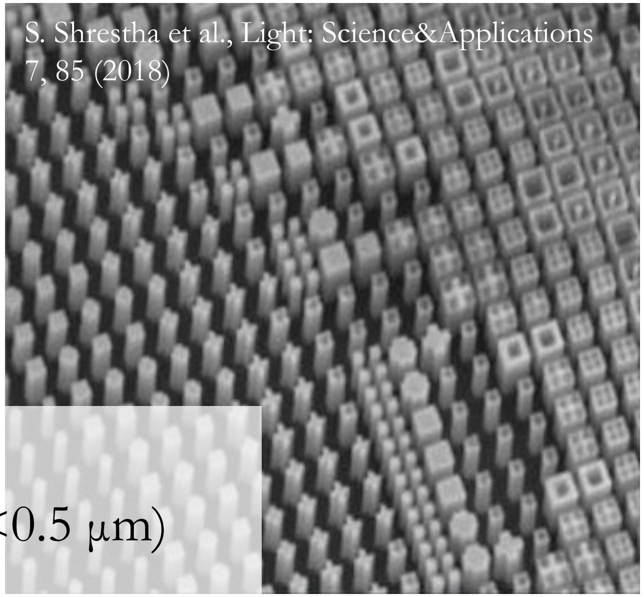
H. Mizuta, Mario A. Garcia-Ramirez, +4 authors S. Oda

Metalenses: the optical (r)evolution





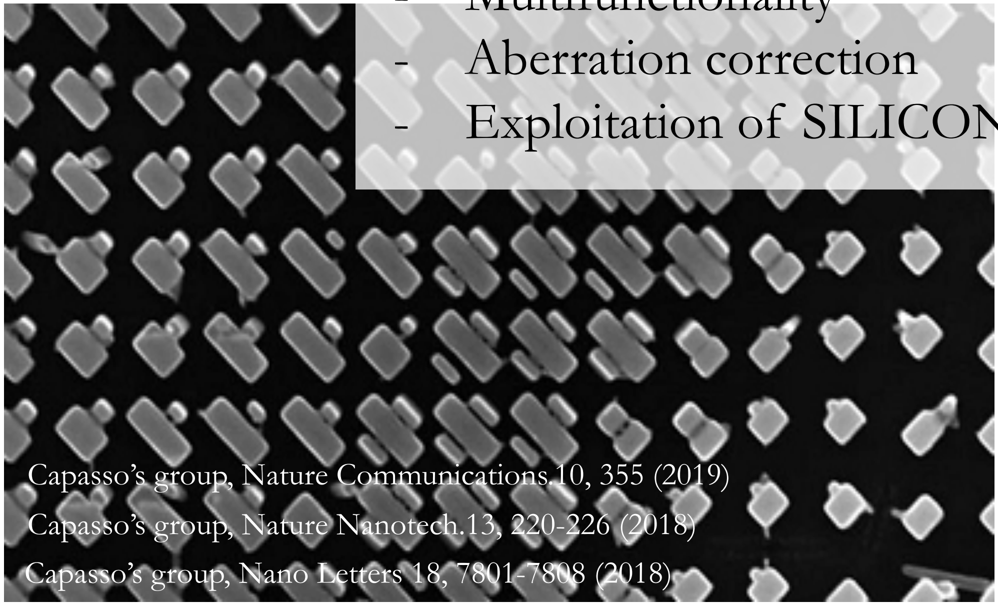
Capasso's group, Science 352, 6290, 1190-1194 (2016)



S. Shrestha et al., Light: Science&Applications 7, 85 (2018)

Revolution in optics:

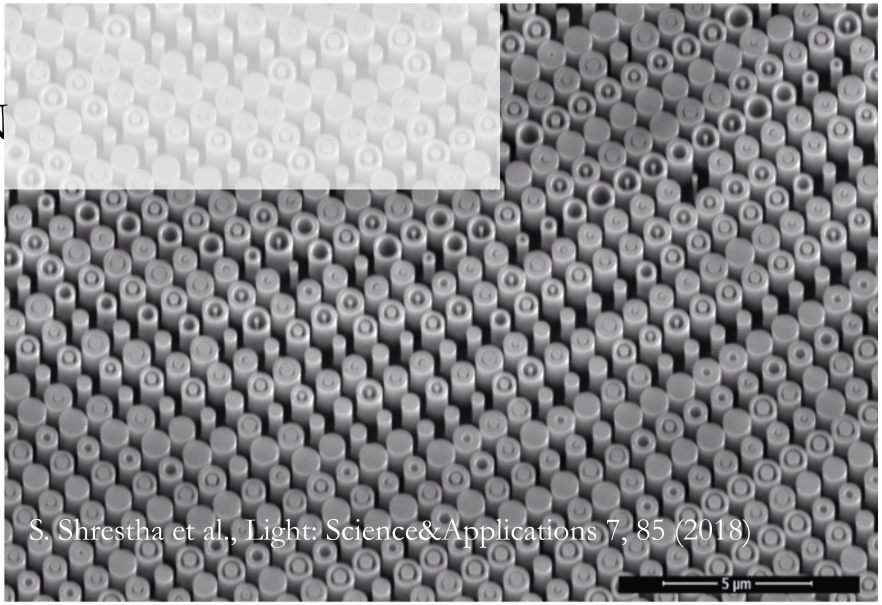
- Flat (2D) optical element (thickness <0.5 μm)
- Multifunctionality
- Aberration correction
- Exploitation of SILICON



Capasso's group, Nature Communications 10, 355 (2019)

Capasso's group, Nature Nanotech.13, 220-226 (2018)

Capasso's group, Nano Letters 18, 7801-7808 (2018)



S. Shrestha et al., Light: Science&Applications 7, 85 (2018)

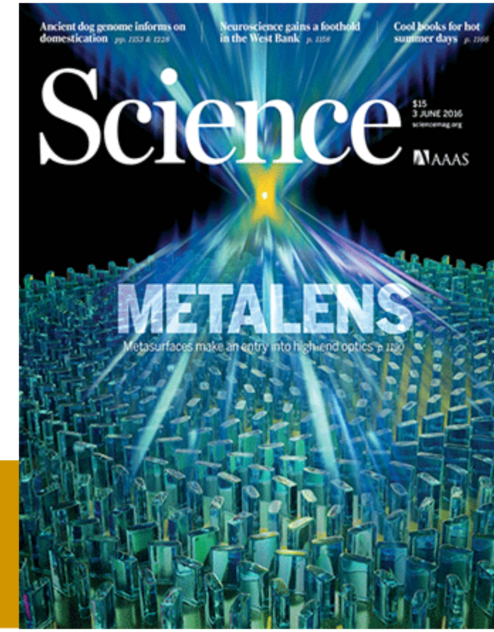
Metalenses: a new paradigm for optics

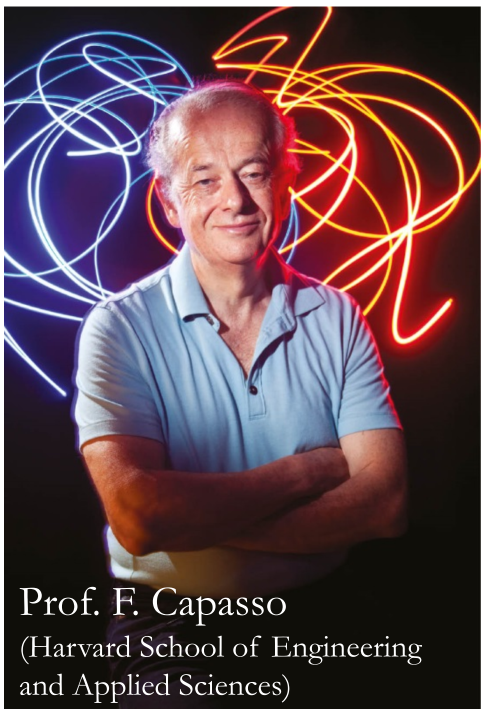
RESEARCH ARTICLE

Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging

Mohammadreza Khorasaninejad[1,*], Wei Ting Chen[1,*], Robert C. Devlin[1,*], Jaewon Oh[1,2], Alexander Y. Zhu[1], Federico Capasso[1,†]

[1]Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA.
[2]University of Waterloo, Waterloo, ON N2L 3G1, Canada.




Prof. F. Capasso
(Harvard School of Engineering and Applied Sciences)

nature nanotechnology

Article | Published: 01 January 2018

A broadband achromatic metalens for focusing and imaging in the visible

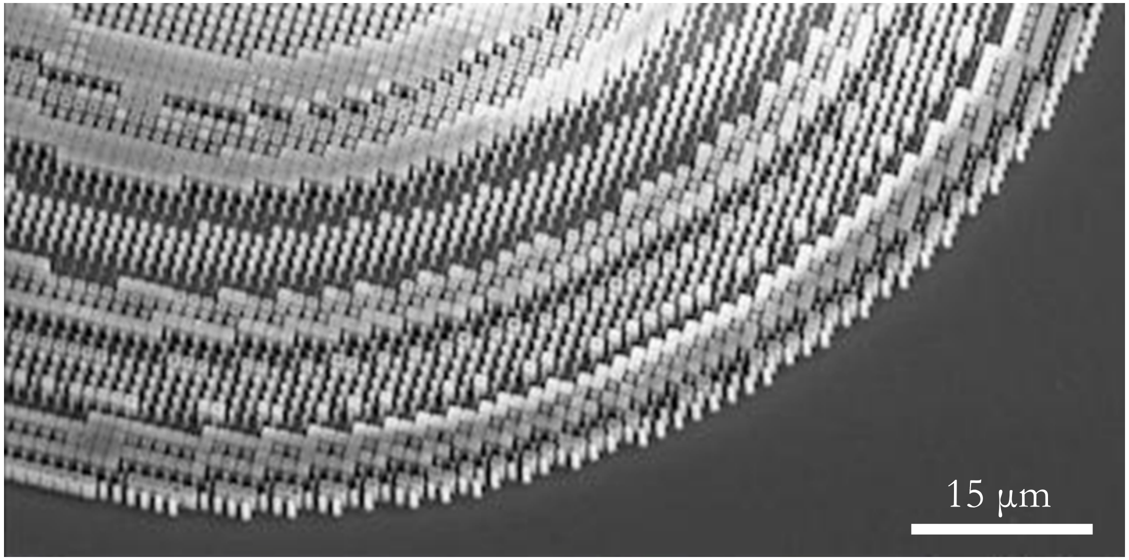
Wei Ting Chen, Alexander Y. Zhu, Vyshakh Sanjeev, Mohammadreza Khorasaninejad, Zhujun Shi, Eric Lee & Federico Capasso

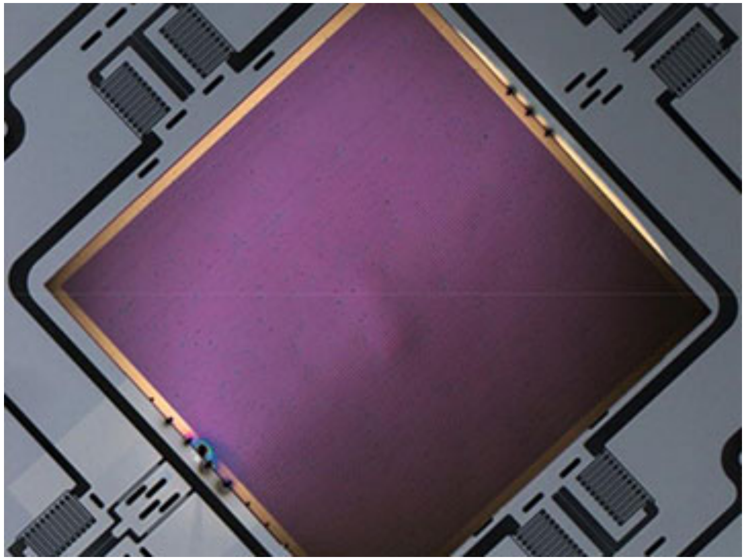
Nature Nanotechnology **13**, 220–226 (2018) | Download Citation

Metalenses: the optical (r)evolution

"The same company/foundry will be able to manufacture the whole module and chip plus optics, disrupting the standard business model. […] This provides the possibility of unifying two industries: semiconductor manufacturing and lens-making. I thereby envision a future of digital optics based on metasurfaces with increased density of optical components and functionality per metasurface […], akin to Moore's law for digital electronics."

F. Capasso, in The Future and Promise of flat optics: a personal perspective, Nanophotonics 7(6), 953-957 (2018).





Next steps: quantum and Artificial Intelligence

UNIVERSITÀ DEGLI STUDI DI PADOVA

Light | Science & Applications

Explore our content ⌄ Journal information ⌄

nature > light: science & applications > review articles > article

Review Article | Open Access | Published: 08 May 2019

Artificial neural networks enabled by nanophotonics

Qiming Zhang, Haoyi Yu, Martina Barbiero, Baokai Wang & Min Gu

Light: Science & Applications **8**, Article number: 42 (2019) | Cite this article

nature photonics

Explore our content ⌄ Journal information ⌄

nature > nature photonics > review articles > article

Review Article | Published: 21 October 2019

Integrated photonic quantum technologies

Jianwei Wang, Fabio Sciarrino, Anthony Laing & Mark G. Thompson

Nature Photonics **14**, 273–284(2020) | Cite this article

DE GRUYTER Nanophotonics 2019; 8(3): 339–366

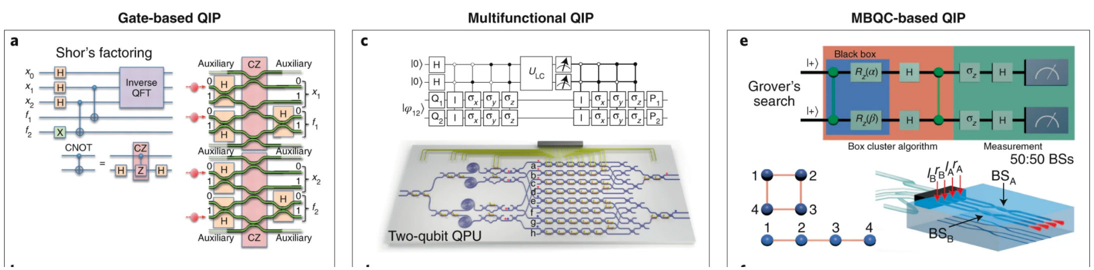
Review article

Kan Yao, Rohit Unni and Yuebing Zheng*

Intelligent nanophotonics: merging photonics and artificial intelligence at the nanoscale

Fig. 4: Quantum information processing and computing with integrated optics.

From: Integrated photonic quantum technologies



Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

iom Istituto Officina dei Materiali

2020 ICOP

ALGEBRA OF LIGHT

Multiplication and Division of the Orbital Angular Momentum

Gianluca Ruffato[1] and Filippo Romanato[1,2]

[1] Department of Physics and Astronomy "G. Galilei", University of Padova, Padova, Italy
[2] IOM-CNR National Laboratory at Elettra Synchrotron, Basovizza Trieste, Italy

Latest research on reconfigurability (2019)

Light | Science & Applications

Explore our content ⌄   Journal information ⌄

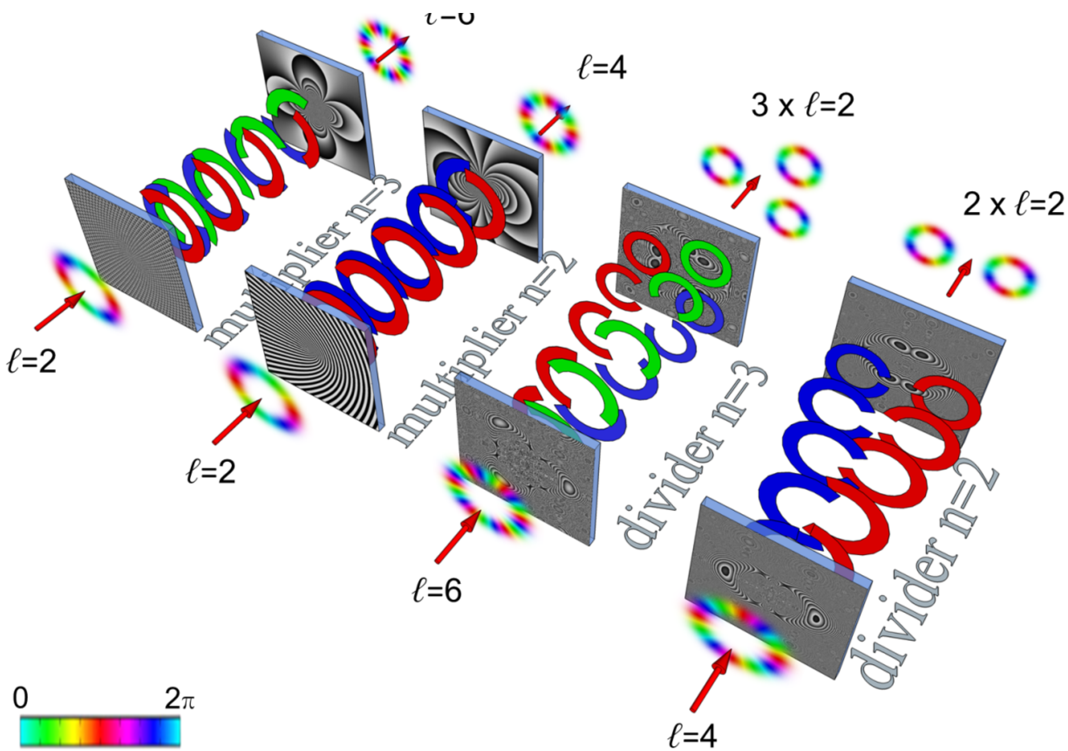
nature > light: science & applications > articles > article

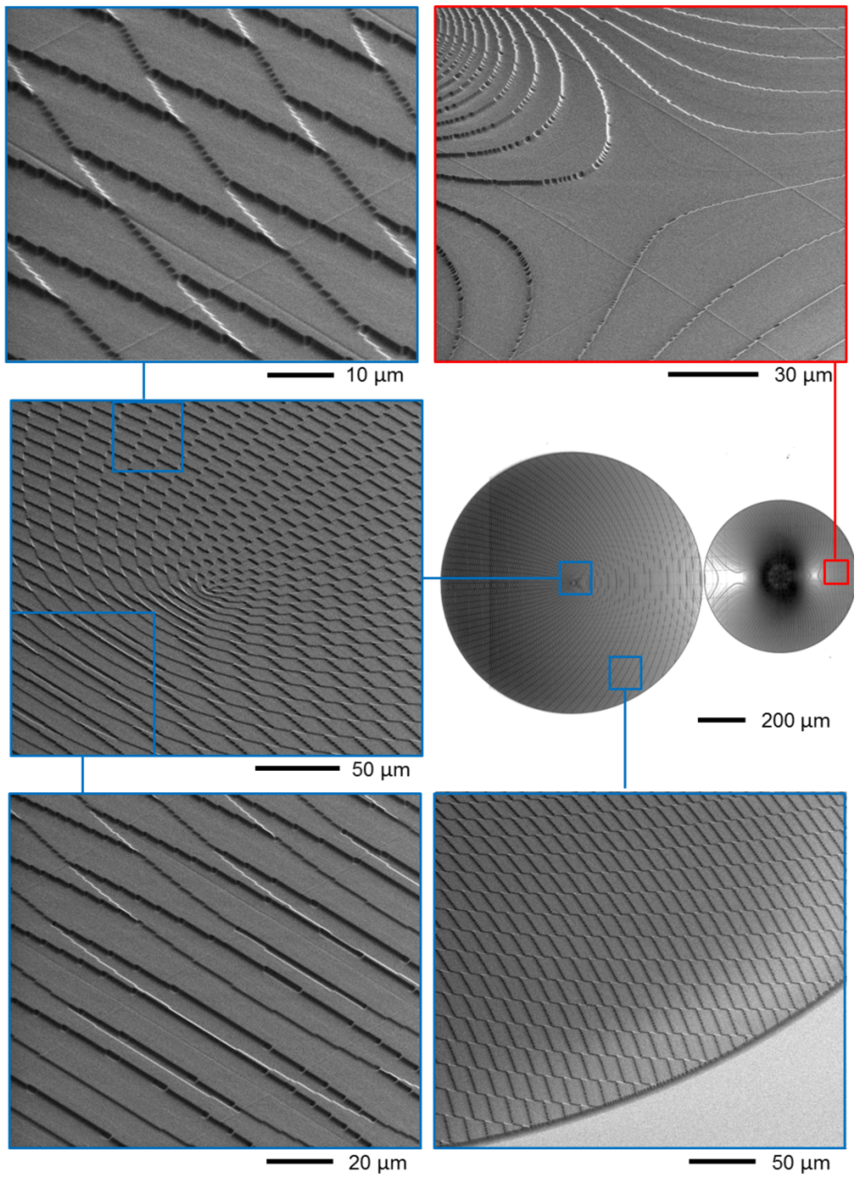
Article | Open Access | Published: 05 December 2019

Multiplication and division of the orbital angular momentum of light with diffractive transformation optics

Gianluca Ruffato, Michele Massari & Filippo Romanato

Light: Science & Applications **8**, Article number: 113 (2019) | Cite this article





PLOS ONE

PUBLISH ABOUT BROWS

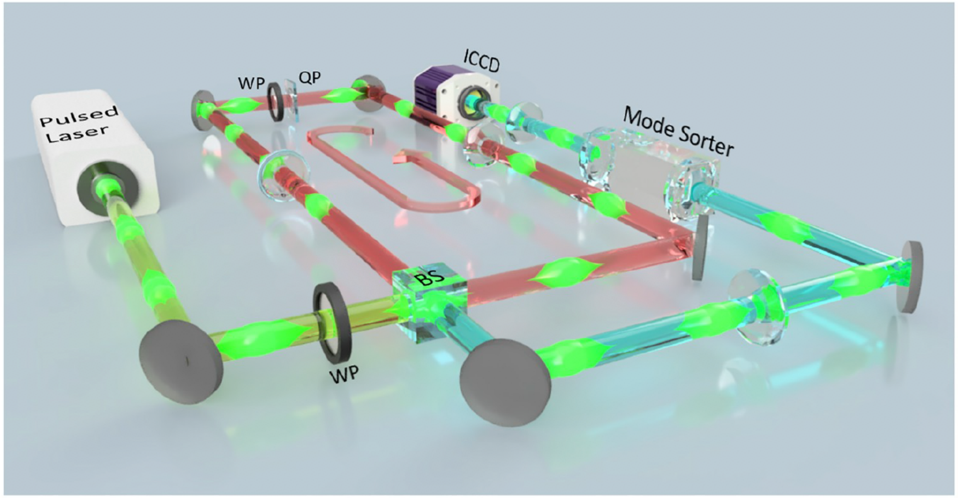
OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

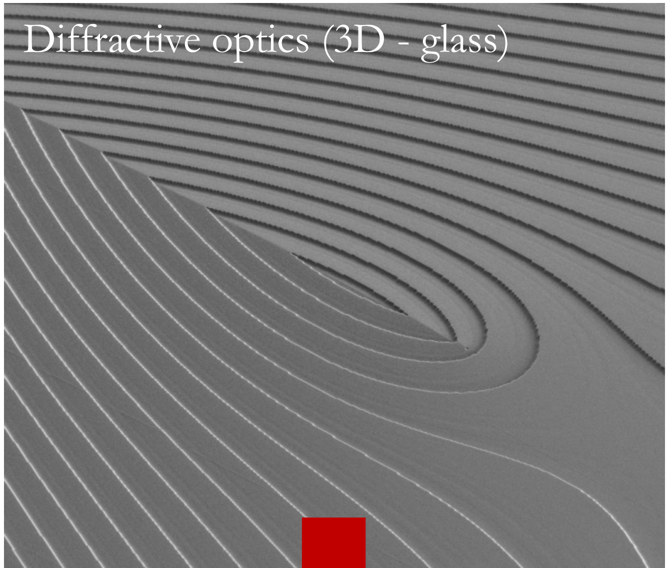
A versatile quantum walk resonator with bright classical light

Bereneice Sephton, Angela Dudley, Gianluca Ruffato, Filippo Romanato, Lorenzo Marrucci, Miles Padgett, Sandeep Goyal, Filippus Roux, Thomas Konrad, Andrew Forbes

Published: April 9, 2019 • https://doi.org/10.1371/journal.pone.0214891



Latest result: metalenses for multiplexing (2019)

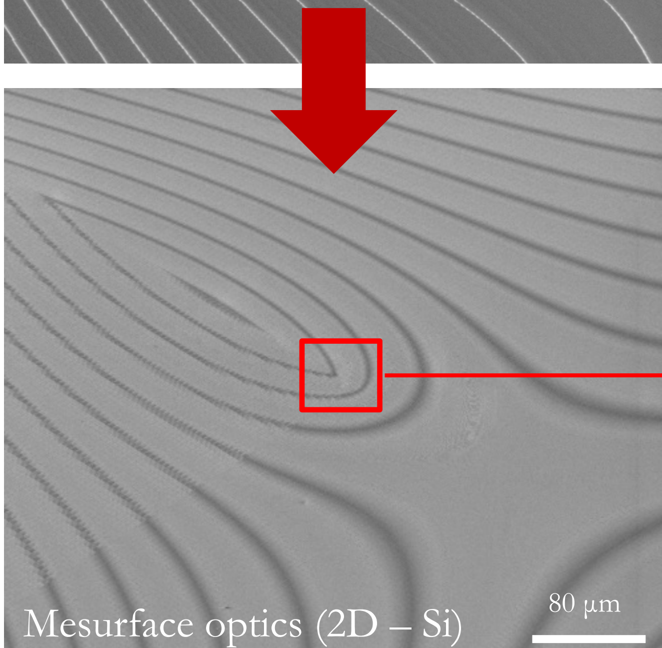


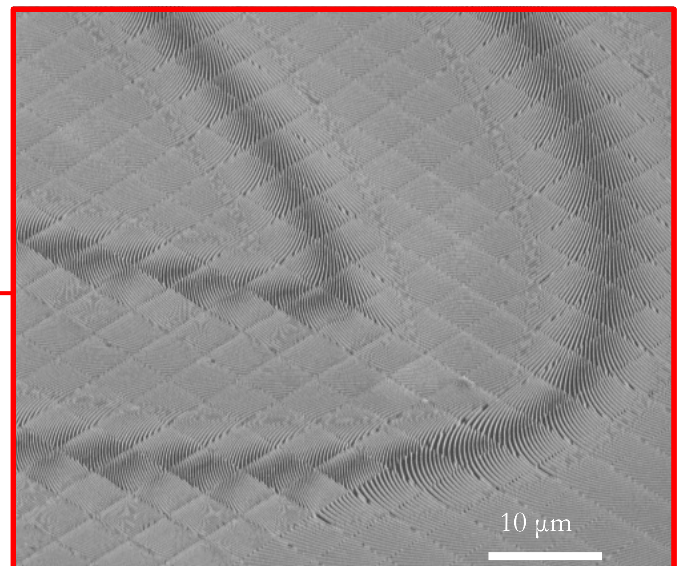
Research Article
Vol. 27, No. 11 | 27 May 2019 | OPTICS EXPRESS 15750
Optics EXPRESS

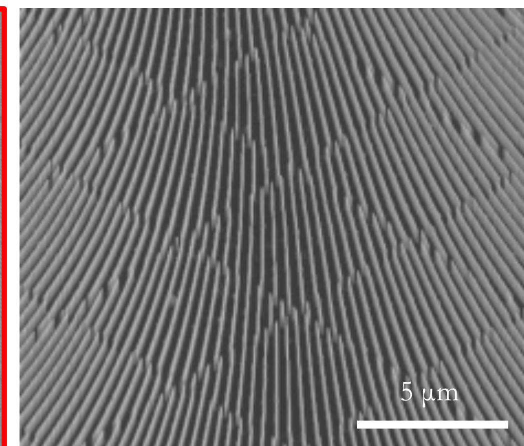
Total angular momentum sorting in the telecom infrared with silicon Pancharatnam-Berry transformation optics

G. RUFFATO,[1,2,4] P. CAPALDO,[2,3] M. MASSARI,[2,3] E. MAFAKHERI,[1,2] AND F. ROMANATO[1,2,3,*]

[1]*Department of Physics and Astronomy 'G. Galilei', University of Padova, via Marzolo 8, 35131 Padova, Italy*
[2]*LANN, Laboratory for Nanofabrication of Nanodevices, EcamRicert, Corso Stati Uniti 4, 35127 Padova, Italy*
[3]*CNR-INFM TASC IOM National Laboratory, S.S. 14 Km 163.5, 34149 Basovizza, Trieste, Italy*



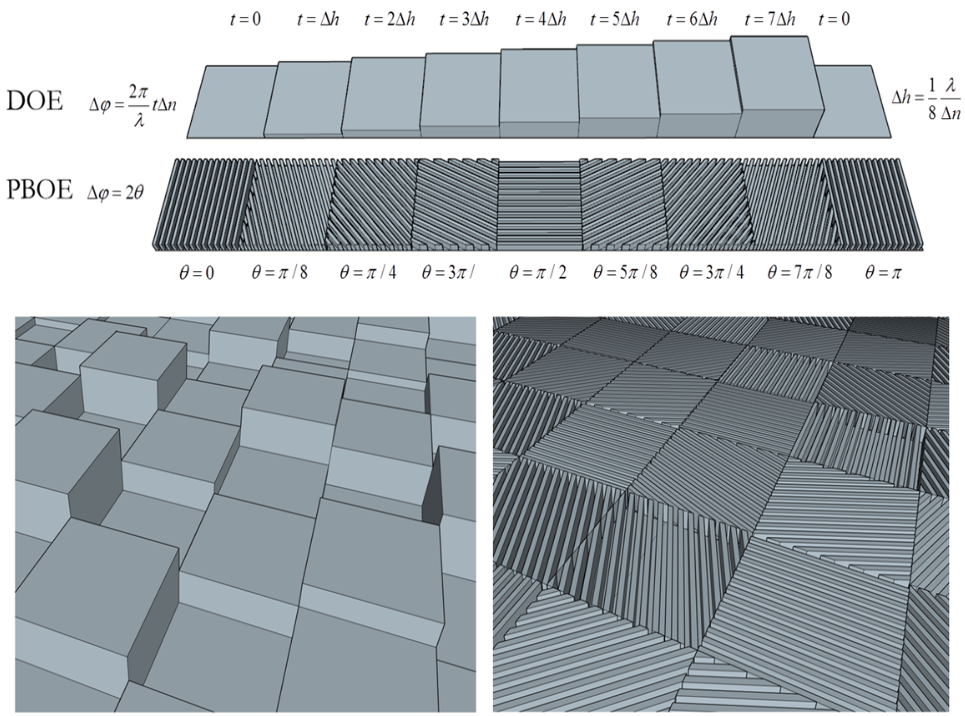


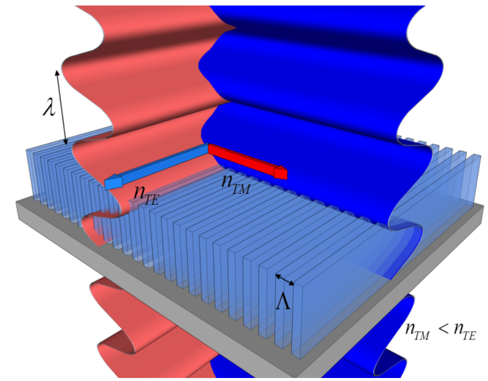


Subwavelength gratings in Silicon

Pancharatnam-Berry optical elements

Università degli Studi di Padova





Diffractive optics as space-variant subwavelength gratings:

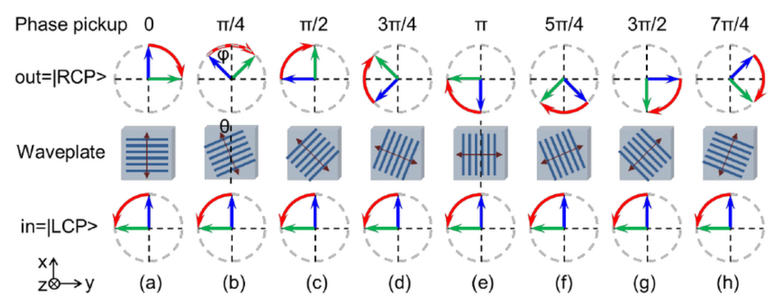
$$T\begin{pmatrix}1\\ i\end{pmatrix}=\cos(\delta/2)\begin{pmatrix}1\\ i\end{pmatrix}-i\sin(\delta/2)e^{+2i\theta}\begin{pmatrix}1\\ -i\end{pmatrix}$$

$$T\begin{pmatrix}1\\ -i\end{pmatrix}=\cos(\delta/2)\begin{pmatrix}1\\ -i\end{pmatrix}-i\sin(\delta/2)e^{-2i\theta}\begin{pmatrix}1\\ i\end{pmatrix}$$

If $\delta=\pi$, the system acts as a pure phase element with polarization conversion:

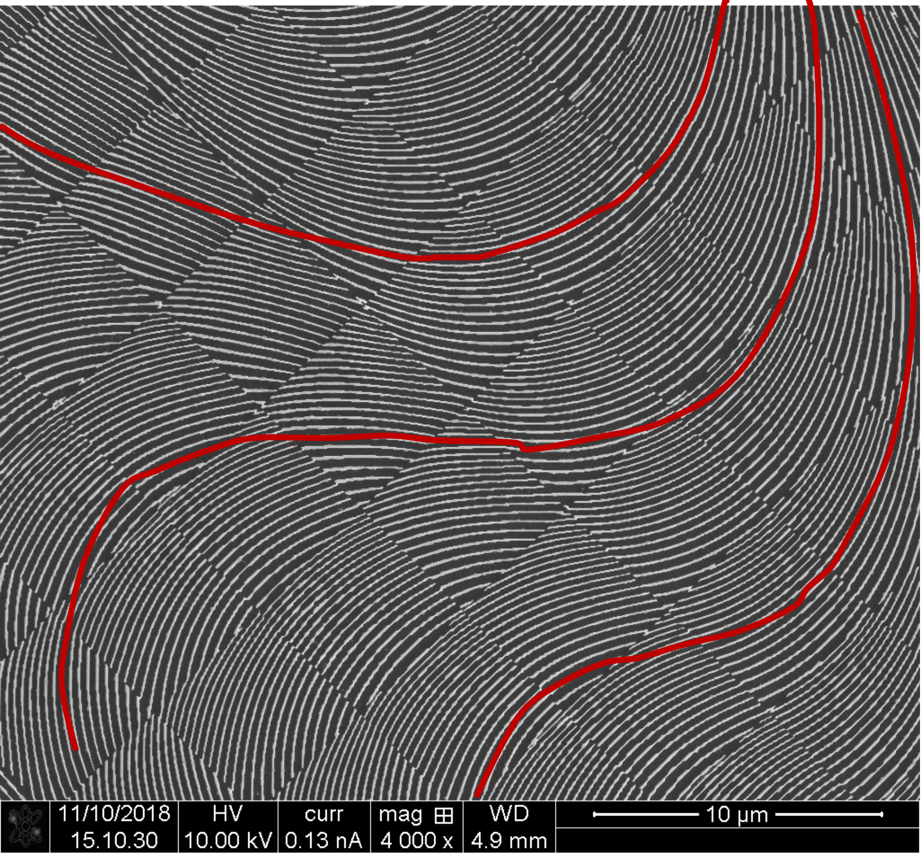
$$T\begin{pmatrix}1\\ i\end{pmatrix}=H\begin{pmatrix}1\\ -i\end{pmatrix}$$

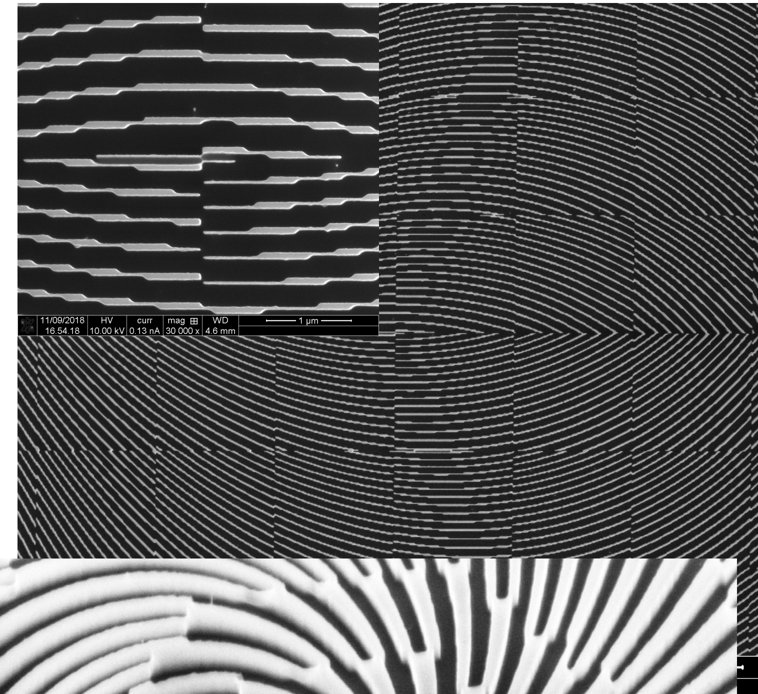
$$T\begin{pmatrix}1\\ -i\end{pmatrix}=-H^*\begin{pmatrix}1\\ i\end{pmatrix} \qquad H(x,y)=\exp\left[2i\theta(x,y)\right]$$

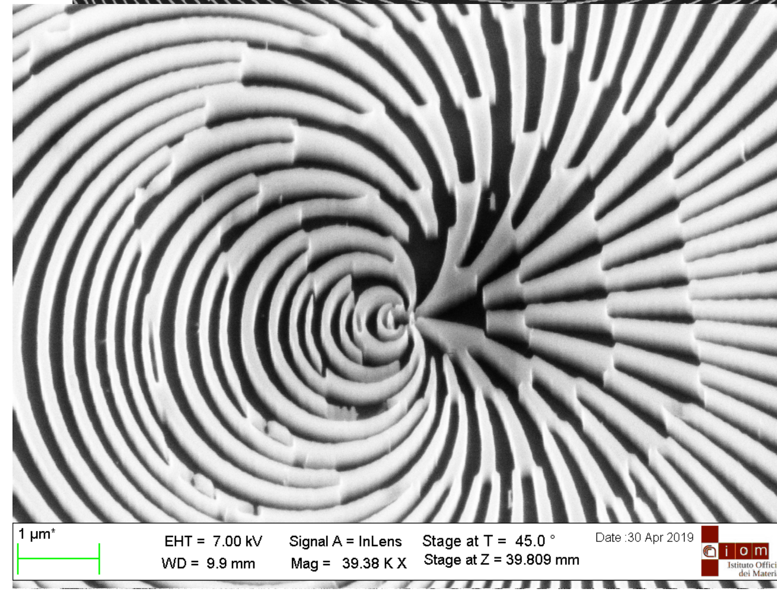


Capaldo, P.,et al & Romanato., Opt. Mat. Express 9(3), 1015-1032 (2019)

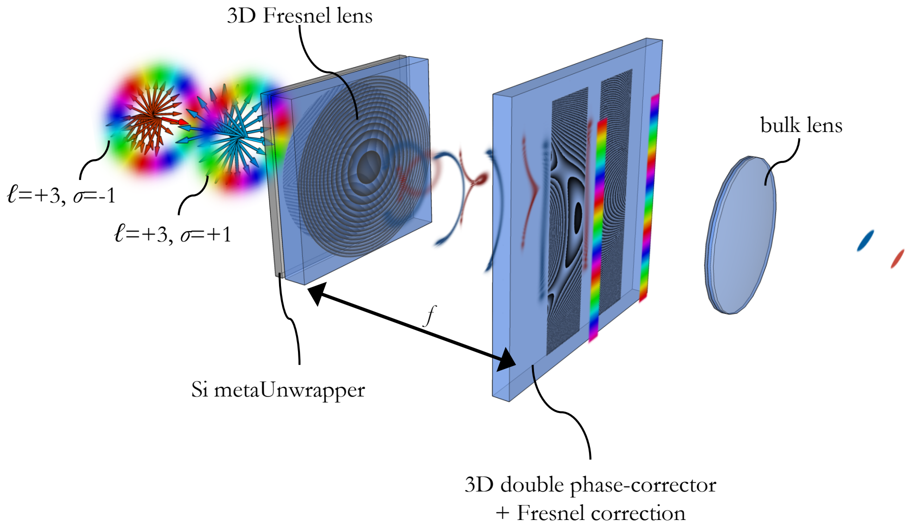
Metalenses structure



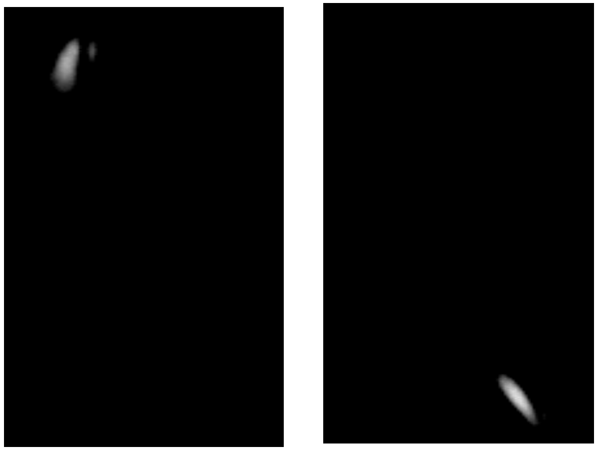




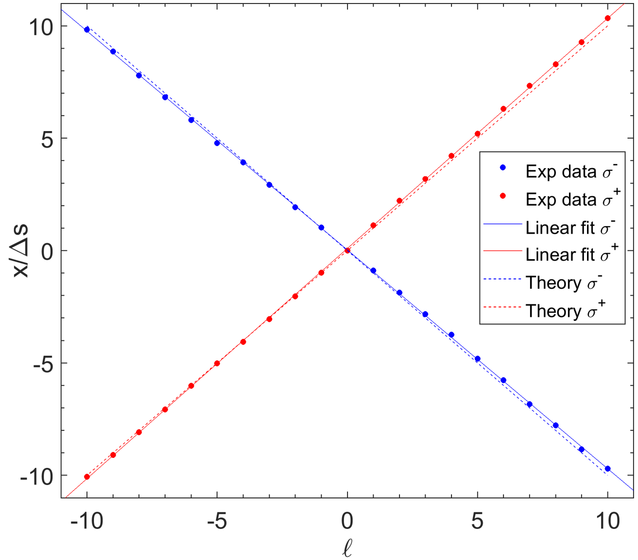
Sorting scheme ℓ in the range from -10 to +10



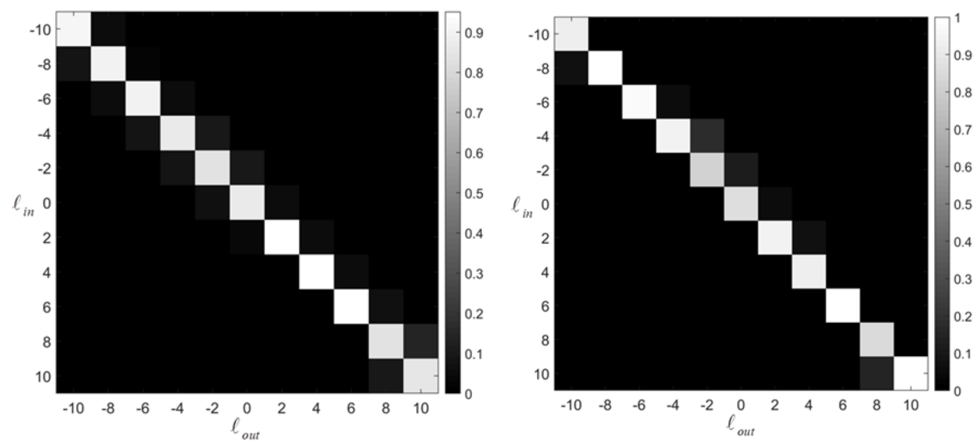
σ=-1 σ=+1



$XT \sim -6dB$



σ=-1 σ=+1

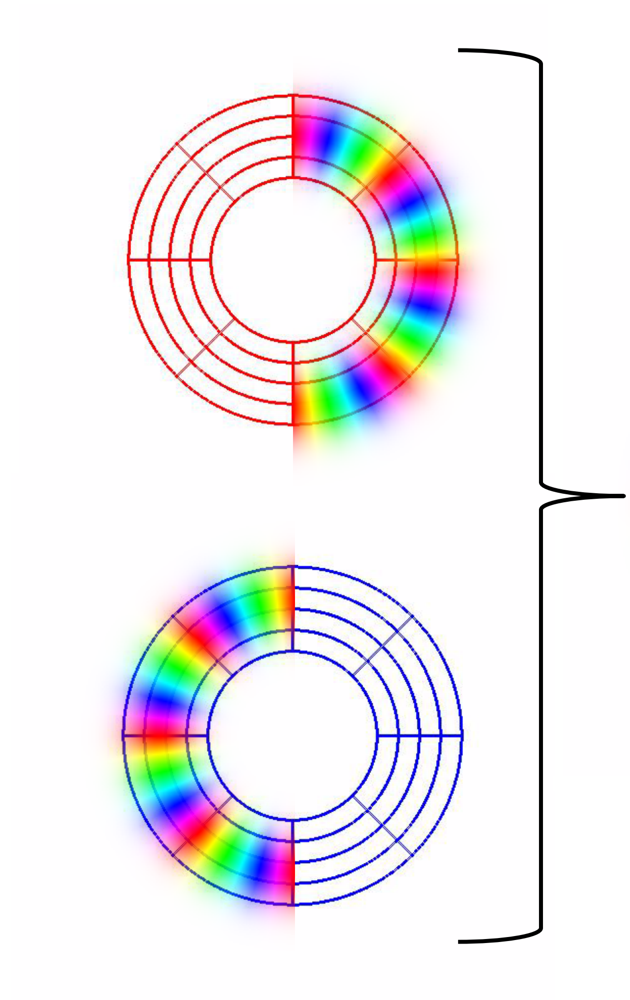


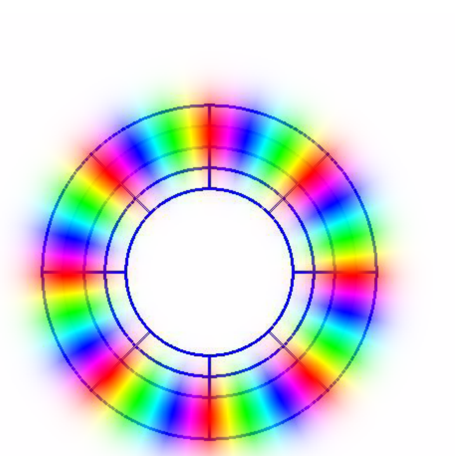
How to multiply the OAM?

The idea is to split the beam and project each copy onto complementary circular sectors:

$n = 2$

$\ell = 4$





$\ell = 8$

Key-element: circular-sector transformation

The transformation maps conformally the whole azimuthal gradient onto a circular sector 2π/n

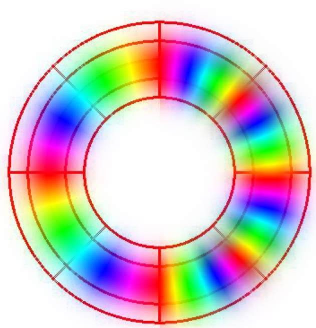
$$\vartheta \longrightarrow \varphi = \frac{\vartheta}{n}$$

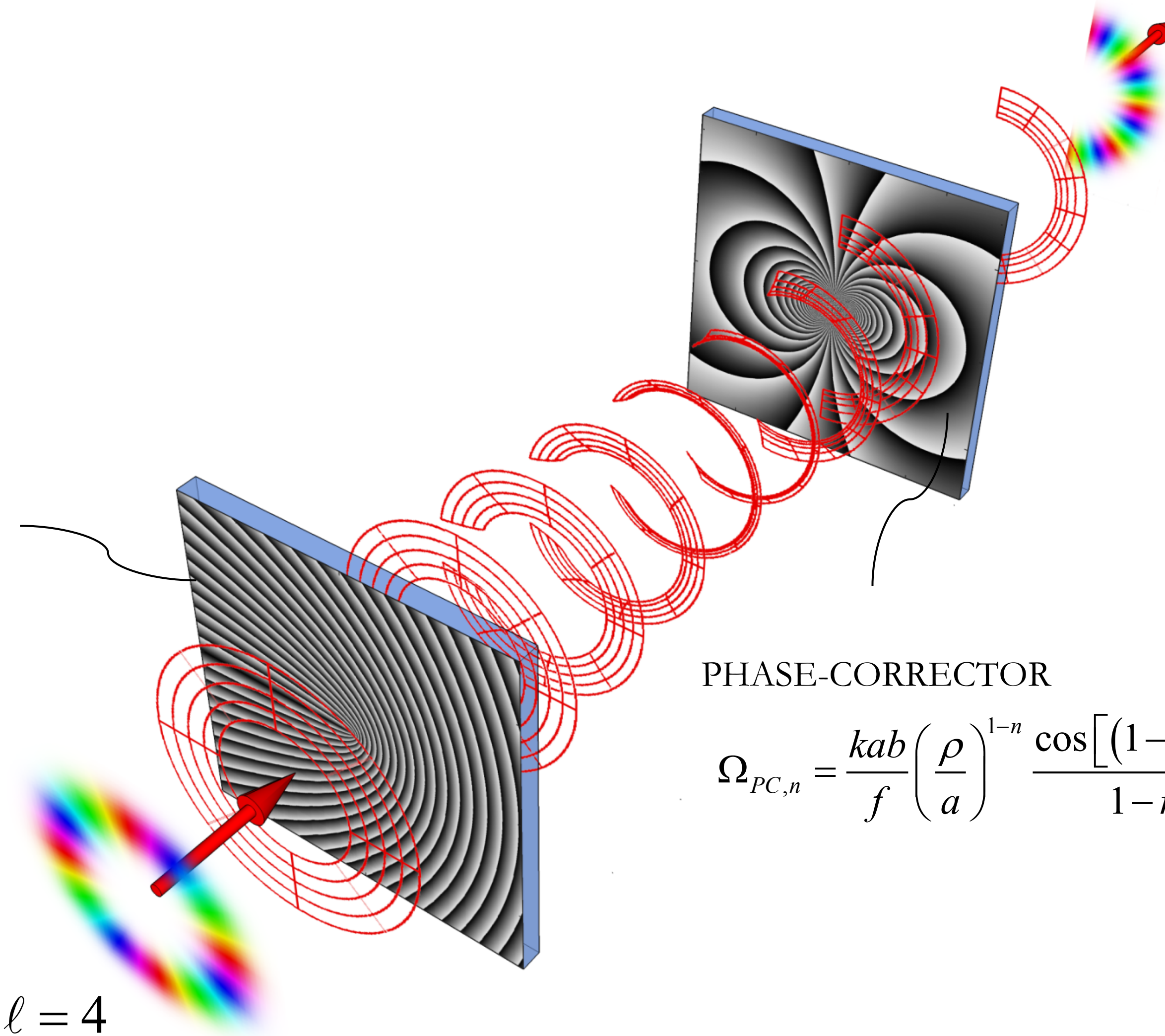
$$r \longrightarrow \rho = a\left(\frac{r}{b}\right)^{-1/n}$$

Two phase elements are required

TRANSFORMER

$$\Omega_{S,n} = \frac{kab}{f}\left(\frac{r}{b}\right)^{1-1/n} \frac{\cos\left[\left(1-\frac{1}{n}\right)\vartheta\right]}{1-\frac{1}{n}}$$





$\ell = 4$

PHASE-CORRECTOR

$$\Omega_{PC,n} = \frac{kab}{f}\left(\frac{\rho}{a}\right)^{1-n} \frac{\cos\left[(1-n)\varphi\right]}{1-n}$$

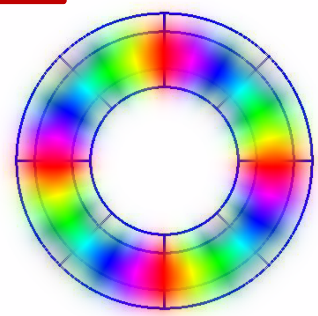
The n-fold multiplier is the combination of n circular-sector transformations:

MULTIPLIER

$$\Omega_{S,n}^{(j)} = \frac{kab}{f}\left(\frac{r}{b}\right)^{1-\frac{1}{n}} \cdot \frac{\cos\left[\vartheta\left(1-\frac{1}{n}\right)+(j-1)\frac{2\pi}{n}\right]}{1-\frac{1}{n}}$$

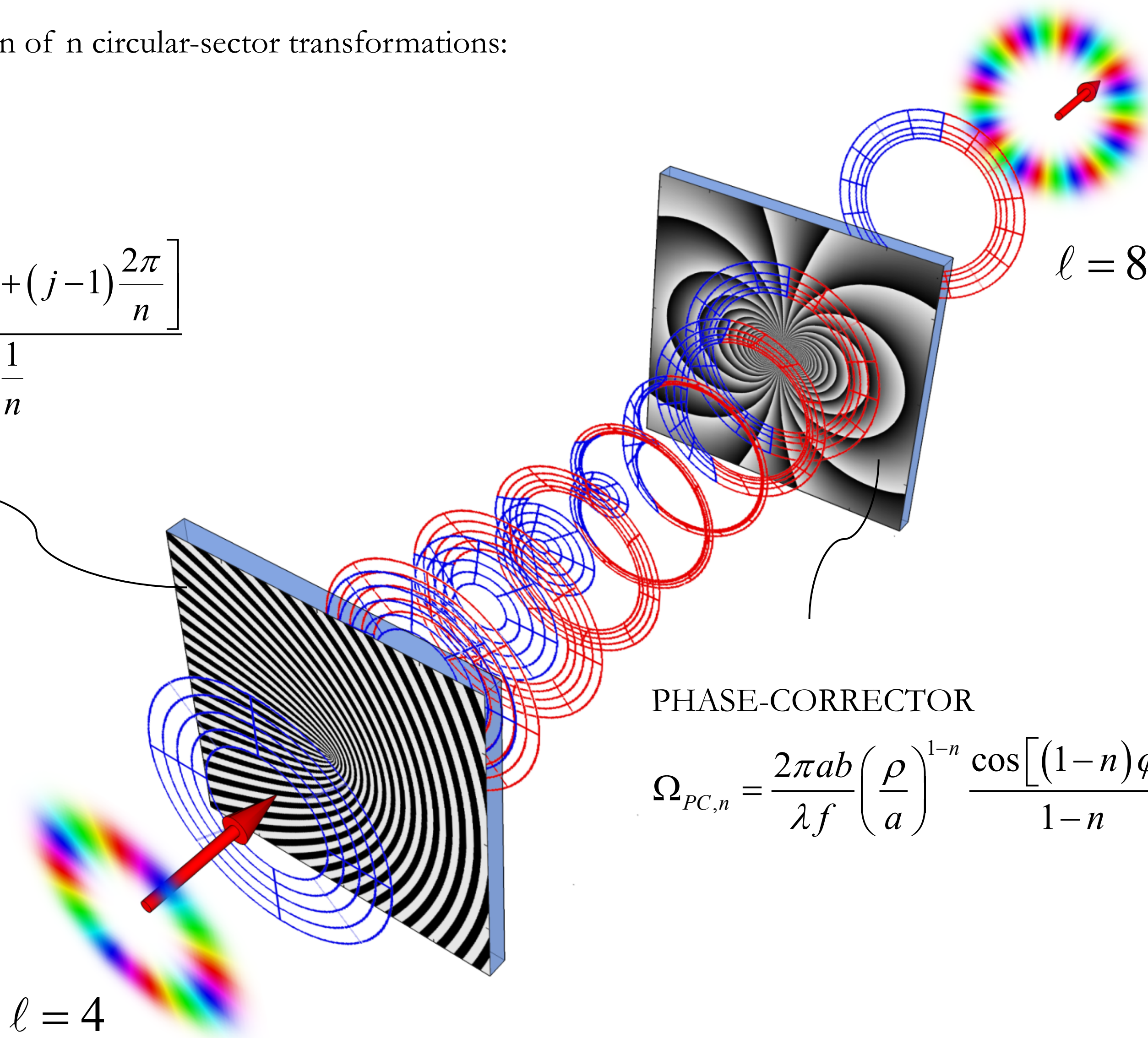
$$\Omega_{M,n} = \arg\left\{\sum_{j=1}^{n} e^{i\Omega_{S,n}^{(j)}}\right\}$$

$n = 2$



$\ell = 4$

$\ell = 8$



PHASE-CORRECTOR

$$\Omega_{PC,n} = \frac{2\pi ab}{\lambda f}\left(\frac{\rho}{a}\right)^{1-n} \frac{\cos\left[(1-n)\varphi\right]}{1-n}$$

The OAM multiplier

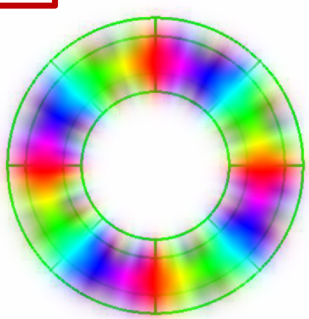
The n-fold multiplier is the combination of n circular-sector transformations:

MULTIPLIER

$$\Omega_{S,n}^{(j)} = \frac{kab}{f}\left(\frac{r}{b}\right)^{1-\frac{1}{n}} \cdot \frac{\cos\left[\vartheta\left(1-\frac{1}{n}\right)+(j-1)\frac{2\pi}{n}\right]}{1-\frac{1}{n}}$$

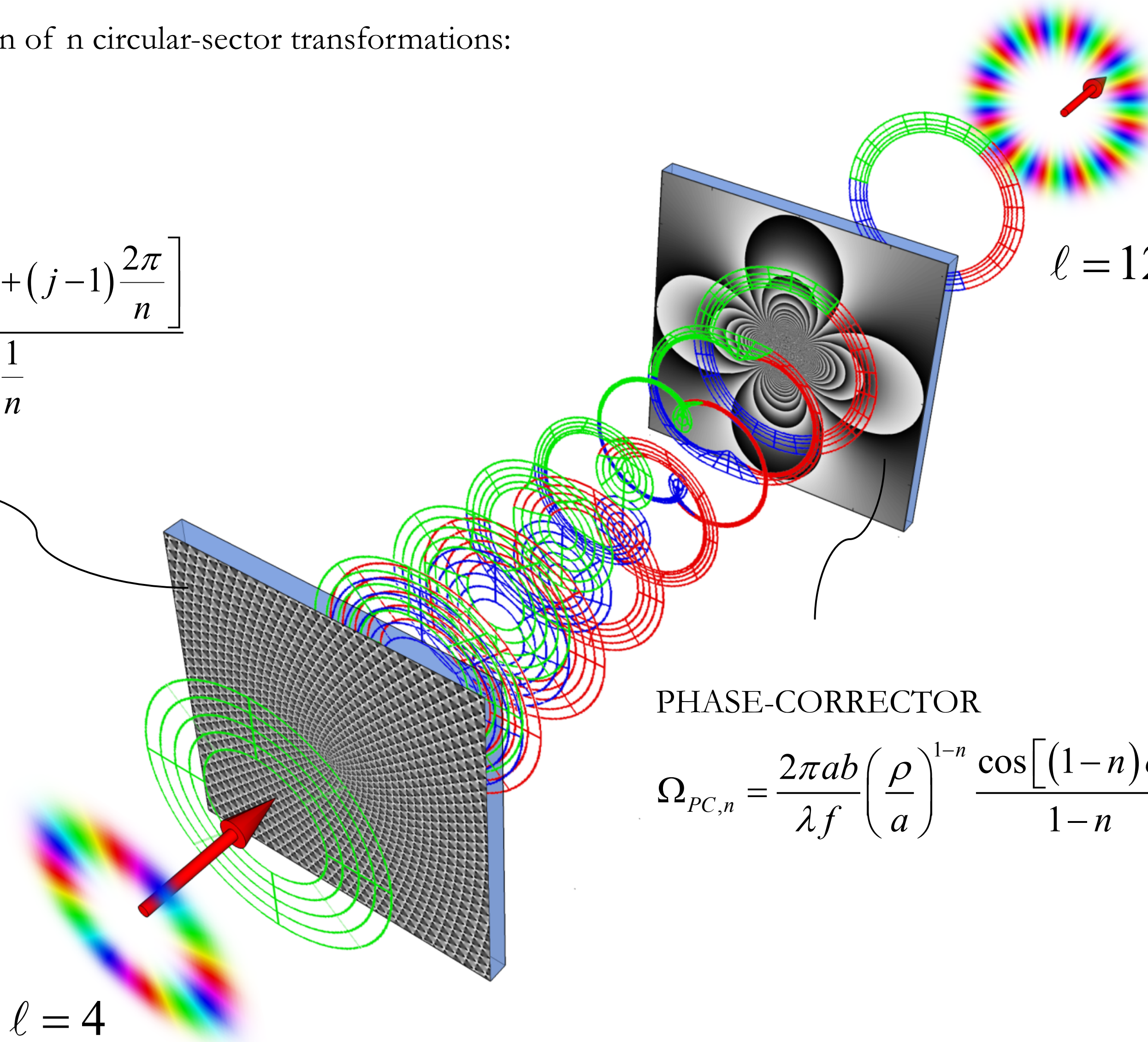
$$\Omega_{M,n} = \arg\left\{\sum_{j=1}^{n} e^{i\Omega_{S,n}^{(j)}}\right\}$$

$n = 3$



$\ell = 4$

$\ell = 12$



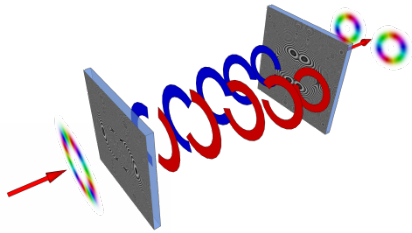
PHASE-CORRECTOR

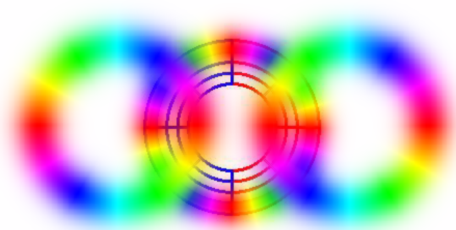
$$\Omega_{PC,n} = \frac{2\pi ab}{\lambda f}\left(\frac{\rho}{a}\right)^{1-n} \frac{\cos\left[(1-n)\varphi\right]}{1-n}$$

The OAM divider

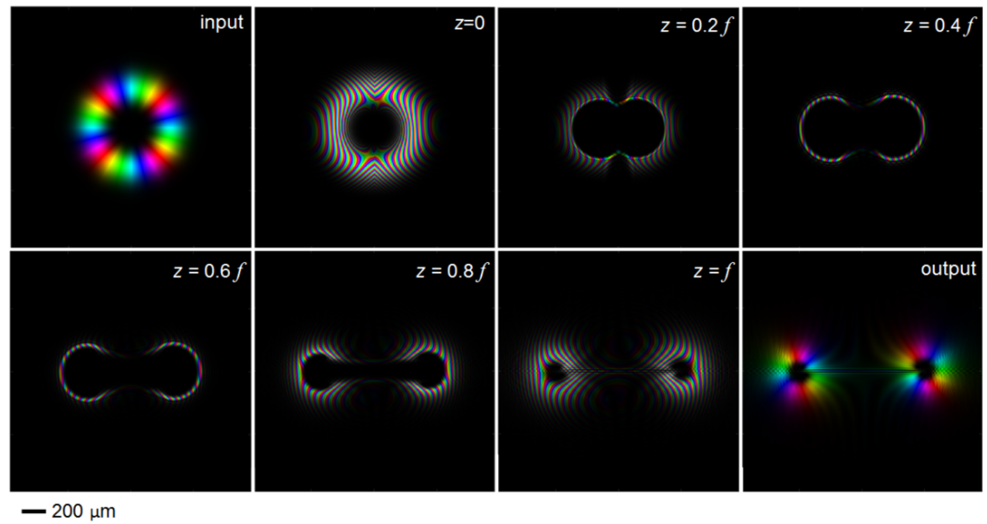
Division is performed using the inverse optical operations. The input beam is split into n OAM beams carrying 1/n the input OAM:

$$n = 1/2$$

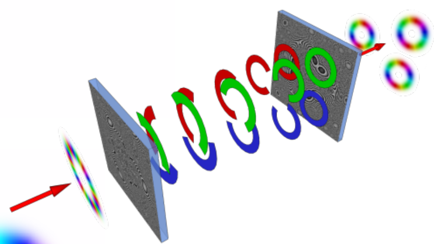


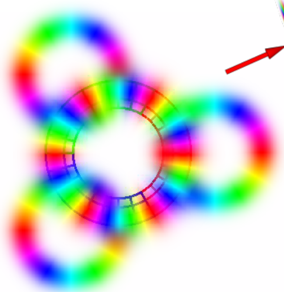


$$\ell = 4 \;\downarrow\; 2\times(\ell = 2)$$

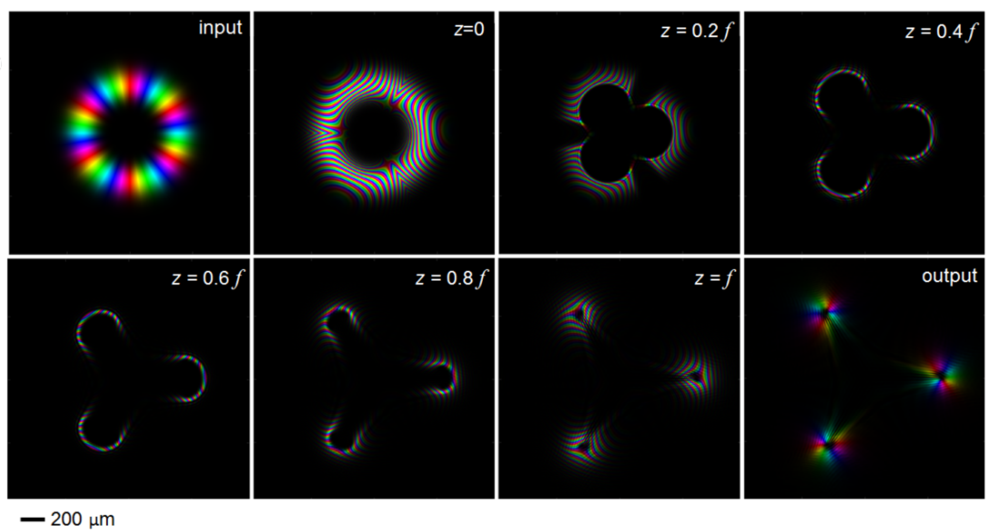


$$n = 1/3$$



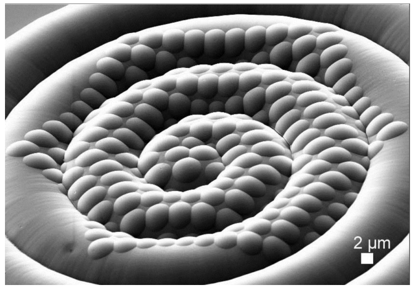


$$\ell = 6 \;\downarrow\; 3\times(\ell = 2)$$

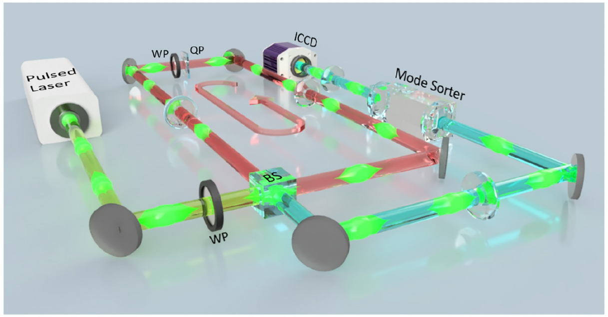


Summary

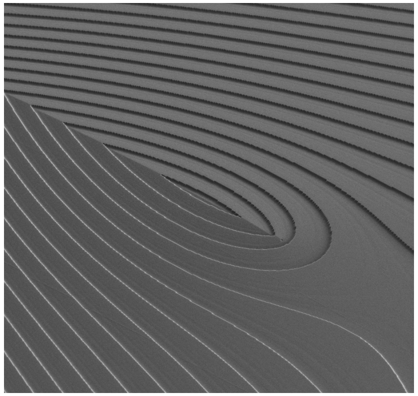
Microlenses



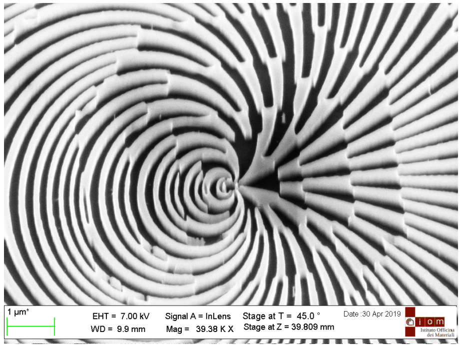
Single photon regime



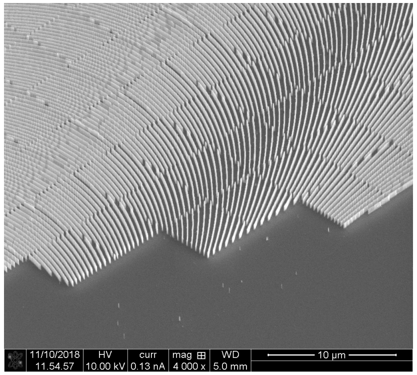
DOE Diffractive Optical Elements



Sub wavelenht control of flat lens

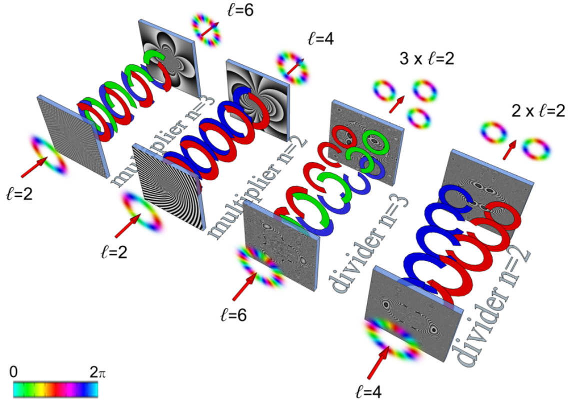


Metalenses



Algebra of light

Multiplication and Division of the Orbital Angular Momentum



Università degli Studi di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

Wish you
a vorticose Thank you !

Prof. Filippo Romanato

Department of Physics and Astronomy, University of Padova,, Italy

IOM-CNR, AREA Science Park, Basovizza-Trieste, Italy

Laboratory for Nanofabrication of Nanodevices, LaNN Padova, Italy

iom Istituto Officina dei Materiali

LaNN

smoptics
siae microelettronica group

FONDAZIONE città della speranza

The research group

Prof. **Filippo Romanato**, *group leader*

Gianluca Ruffato, RTDA, DFA
Michele Massari, *Post-doc,* CNR
Erfan Mafakheri, *Post-doc,* CNR
Giulia Borile, *Post-doc,* CdS
Pietro Capaldo, *Post-doc,* CNR
Andrea Filippi, *PhD student,* DFA

Contacts
e-mail: *gianluca.ruffato@unipd.it*
e-mail: *filippo.romanato@unipd.it*
http://www.lann.it
http://groups.dfa.unipd.it/nanodevices/index.html