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Metafibre Optics: Principles, Fabrication, and Applications

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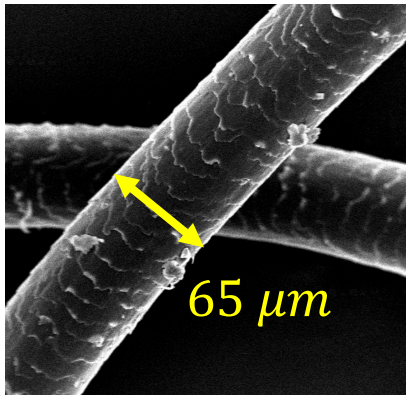
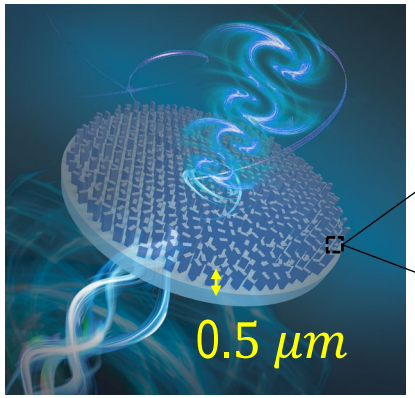
Light manipulation via ultrathin metasurfaces

N. Yu, et. al., *Science*. **334**, 333 (2011). S. Sun, et. al., *Nano Lett.* **12**, 6223 (2012).

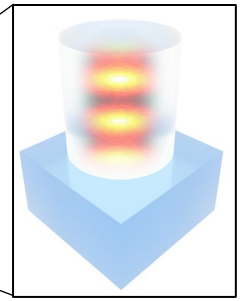
Human hair



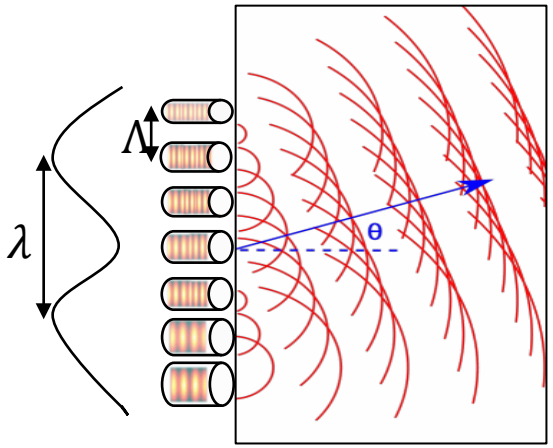
Metasurface



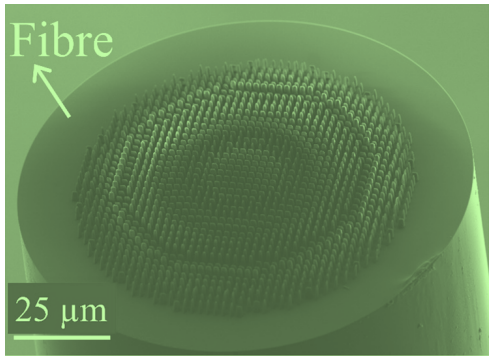
Meta-atom

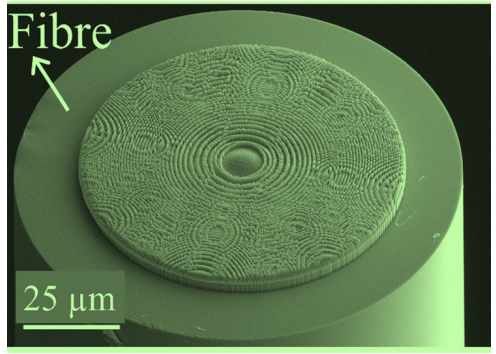


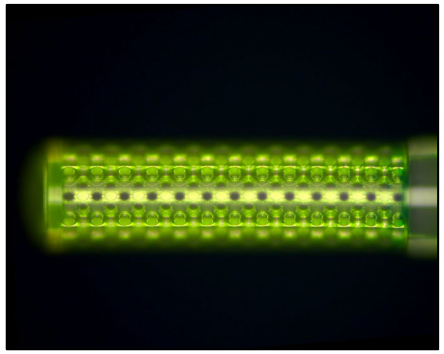
Arbitrary light steering



3D laser nanoprinted metafibre







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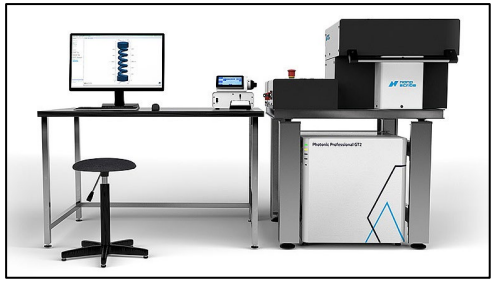

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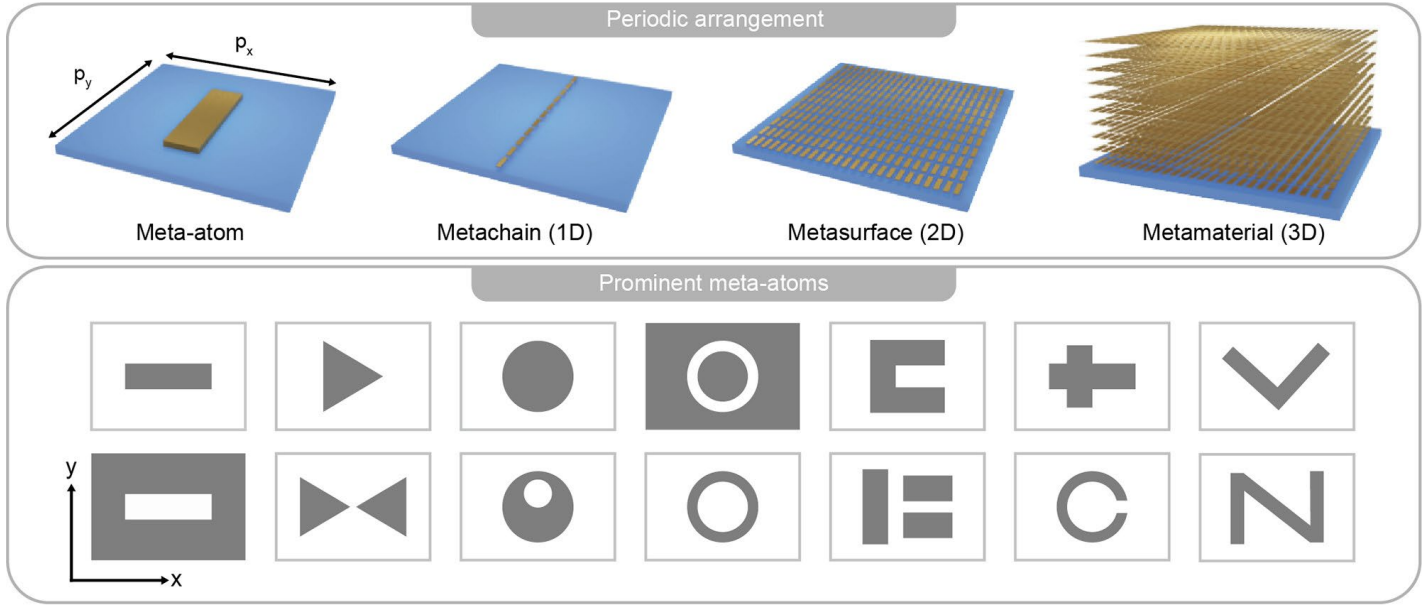
Metasurface examples



E. Cortes, F. J. Wendisch, L. Sortino, A. Mancini, S. Ezendam, S. Saris, L. D. S. Menezes, A. Tittl, H. Ren, S. A. Maier, Metasurfaces for energy conversion, ***Chem. Rev.*** 122, 15082–15176 (2022).

CHEMICAL REVIEWS

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Optical Metasurfaces for Energy Conversion

Emiliano Cortés,*,# Fedja J. Wendisch,# Luca Sortino,# Andrea Mancini, Simone Ezendam, Seryio Saris, Leonardo de S. Menezes, Andreas Tittl, Haoran Ren, and Stefan A. Maier*

Cite This: *Chem. Rev.* 2022, 122, 15082–15176 Read Online

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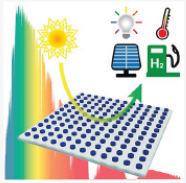
ABSTRACT: Nanostructured surfaces with designed optical functionalities, such as metasurfaces, allow efficient harvesting of light at the nanoscale, enhancing light–matter interactions for a wide variety of material combinations. Exploiting light-driven matter excitations in these artificial materials opens up a new dimension in the conversion and management of energy at the nanoscale. In this review, we outline the impact, opportunities, applications, and challenges of optical metasurfaces in converting the energy of incoming photons into frequency-shifted photons, phonons, and energetic charge carriers. A myriad of opportunities await for the utilization of the converted energy. Here we cover the most pertinent aspects from a fundamental nanoscopic viewpoint all the way to applications.



CONTENTS

1. Introduction 15083
2. Fundamentals 15084
2.1. Light–Matter Interaction: The Basics 15084
2.1.1. Introduction to Optical Constants 15084
2.1.2. Light Absorption in Metals and Semiconductors 15085
2.1.3. Light Scattering by Small Particles 15086
2.2. Plasmonic and Dielectric Metasurfaces 15086
2.2.1. Individual Plasmonic and Dielectric Resonators 15086
2.2.2. Periodic Arrangements of Plasmonic and Dielectric Resonators 15092
2.2.3. Hybrid Metasurfaces 15093
2.3. Fabrication and Design of Metasurfaces 15097
2.3.1. High-Resolution Lithographic Techniques 15098
2.3.2. Scalable and High-Throughput Lithographic Techniques 15100
2.3.3. Self-Assembly 15100
2.3.4. Three-Dimensional Techniques 15100
2.3.5. Rational Design of Metasurfaces: Inverse Design and Artificial Intelligence 15102
3. Photon–Photon Energy Conversion 15103
3.1. Fundamentals of Nonlinear Optical Responses 15103
3.1.1. $\chi^{(2)}$ Processes 15104
3.1.2. $\chi^{(3)}$ Processes 15104
3.1.3. Raman Scattering 15105
3.2. Nonlinear Interactions with Metasurfaces 15107
3.3. Metasurfaces for Enhancing Upconversion and Quantum Cutting 15109
3.3.1. Upconversion 15110
3.3.2. Quantum Cutting 15113
3.4. Section Summary 15114
4. Photon–Phonon Energy Conversion 15115
4.1. Photon-to-Heat and Heat-to-Photon Energy Conversion 15116
4.1.1. Thermal Nanophotonics 15116
4.1.2. Metasurface-Controlled Far-Field Thermal Emission 15119
4.1.3. Metasurfaces for Radiative Cooling and IR Camouflage 15120
4.1.4. Near-Field Radiative Energy Transfer 15121
4.2. Photon–Acoustic Phonon Energy Conversion 15122
4.3. Photon–Optical Phonon Energy Conversion 15125
4.3.1. Metasurfaces for Surface Phonon Polariton Engineering 15125
4.3.2. Metasurfaces for Surface Enhanced Infrared Absorption and Surface Enhanced Raman Spectroscopy 15127
4.4. Section Summary 15130
5. Photon–Electron Energy Conversion 15130
5.1. General Requirements for Photon–Electron Energy Conversion 15131
5.1.1. Light Absorption 15131
5.1.2. Charge Carrier Transport and Separation 15131
5.1.3. Evaluation of Device Performance 15132
5.2. Metasurfaces for Photovoltaics 15134
5.3. Metasurfaces for Photodetectors 15137

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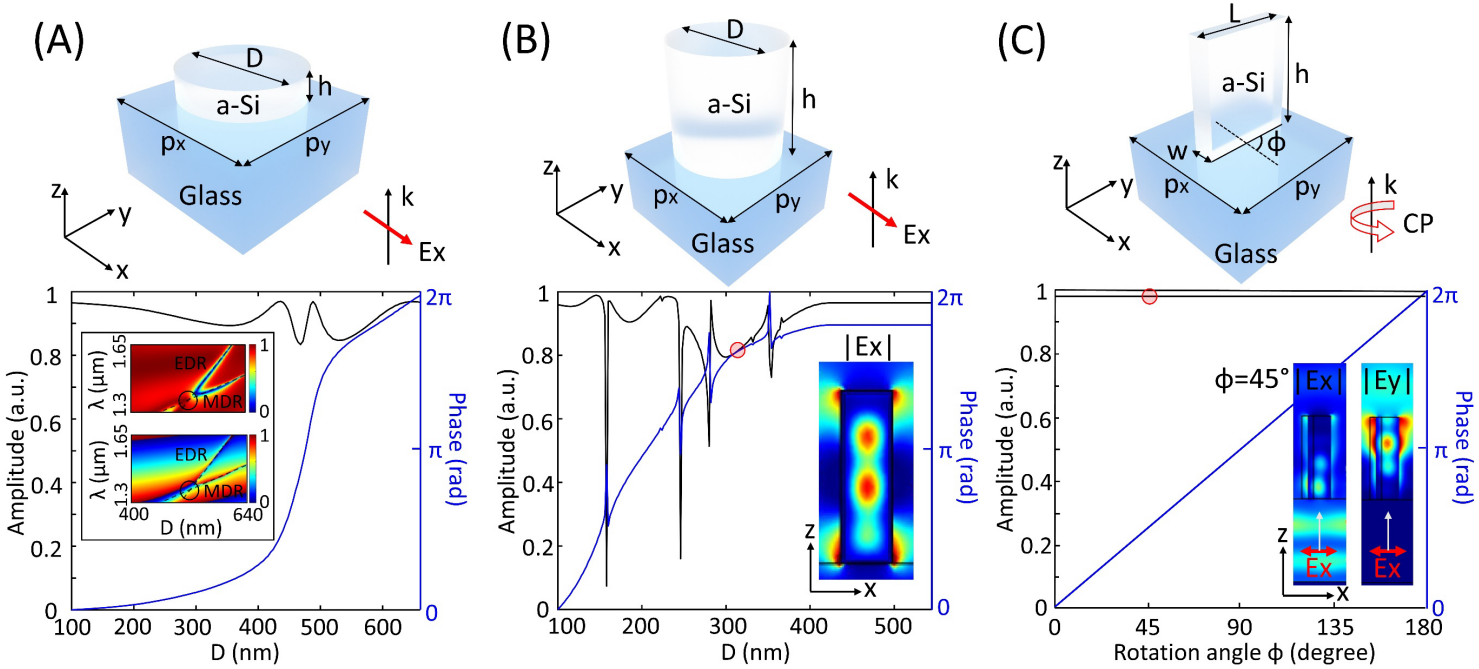
Metasurface design – dielectric modes



H. Ren, S. A. Maier, Nanophotonic materials for twisted-light manipulation, ***Adv. Mater.*** 2106692, (2022).

REVIEW

ADVANCED MATERIALS
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Nanophotonic Materials for Twisted-Light Manipulation

Haoran Ren and Stefan A. Maier**

Twisted light, an unbounded set of helical spatial modes carrying orbital angular momentum (OAM), offers not only fundamental new insights into structured light–matter interactions, but also a new degree of freedom to boost optical and quantum information capacity. However, current OAM experiments still rely on bulky, expensive, and slow-response diffractive or refractive optical elements, hindering today's OAM systems to be largely deployed. In the last decade, nanophotonics has transformed the photonic design and unveiled a diverse range of compact and multifunctional nanophotonic devices harnessing the generation and detection of OAM modes. Recent metasurface devices developed for OAM generation in both real and momentum space, presenting design principle and exemplary devices, are summarized. Moreover, recent development of whispering-gallery-mode-based passive and tunable microcavities, capable of extracting degenerate OAM modes for on-chip vortex emission and lasing, is summarized. In addition, the design principle of different plasmonic devices and photodetectors recently developed for on-chip OAM detection is discussed. Current challenges faced by the nanophotonic field for twisted-light manipulation and future advances to meet these challenges are further discussed. It is believed that twisted-light manipulation in nanophotonics will continue to make significant impact on future development of ultracompact, ultrahigh-capacity, and ultrahigh-speed OAM systems-on-a-chip.

1. Introduction

The development of miniaturized photonic devices to generate, transmit, manipulate, and retrieve increasingly enormous amounts of data for high-capacity optical networks is vitally important. During the 1980s, optical communication experiments driven by wavelength-division multiplexing were performed on large optical tables using expensive devices that were not meant for practical communication systems. The development of cost-effective, integrated devices then followed, to enable wavelength-division multiplexing to be widely deployed. However, present-day optical communication systems using wavelength-division multiplexing are heading toward a capacity limit (**Figure 1**A). To further scale-up the capacity of photonic devices, twisted light multiplexing, based on an unbounded set of orbital angular momentum (OAM) modes, has been recognized as a viable space-division multiplexing approach to significantly increasing the multiplexing capacity of future optical communication systems.[1] In this context, OAM multiplexing has been employed for optical communications in free space,[2,3] optical fibers,[4] and quantum communications.[5–7] It should be mentioned, however, OAM modes are only a subset of the Laguerre–Gaussian modes of structured light,[8] and increasing optical multiplexing capacity can also be realized from other sets of orthogonal spatial modes.[9] However, owing to the fast growing OAM research field, a broad range of photonic devices used for the OAM generation, multiplexing, detection, and demultiplexing have been developed, offering the OAM a compelling advantage to be largely deployed in future photonic information systems.

The angular momentum is a property to describe the rotation of an object around an axis. When it applies to light beams, the angular momentum **L** can be defined as the cross-product between the position vector **r** and the linear momentum vector

$$\mathbf{L} = \varepsilon_0 \int \mathbf{r} \times (\mathbf{E} \times \mathbf{B}) \mathrm{d}^3 r \quad (1)$$

where ε_0 is the vacuum permittivity, **E** and **B** are the vectorial electric and magnetic fields of an electromagnetic wave. The angular momentum can be separated in the paraxial limit into two parts: the spin angular momentum (SAM) associated with circular polarization, and the OAM manifested by an optical vortex beam with a helical wavefront.[10] For both paraxial and

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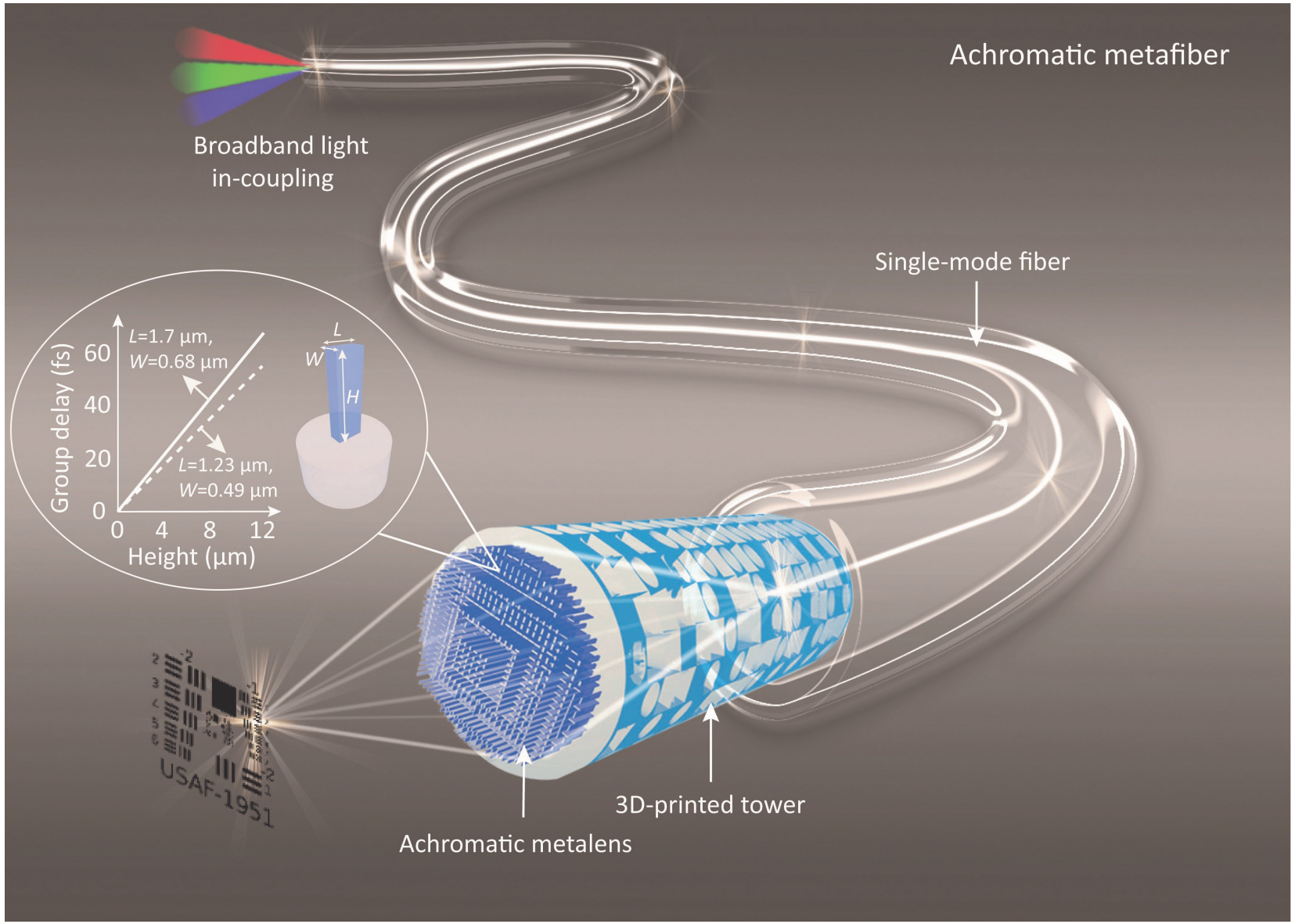
An achromatic metafibre for focusing and imaging across the entire telecommunication range



H. Ren, J. Jang, C. Li, A. Aigner, M. Plidschun, J. Kim, J. Rho, M. A. Schmidt, and S. A. Maier, An achromatic metafiber for focusing and imaging across the entire telecommunication range, ***Nat. Commun.***, 13, 4183 (2022).

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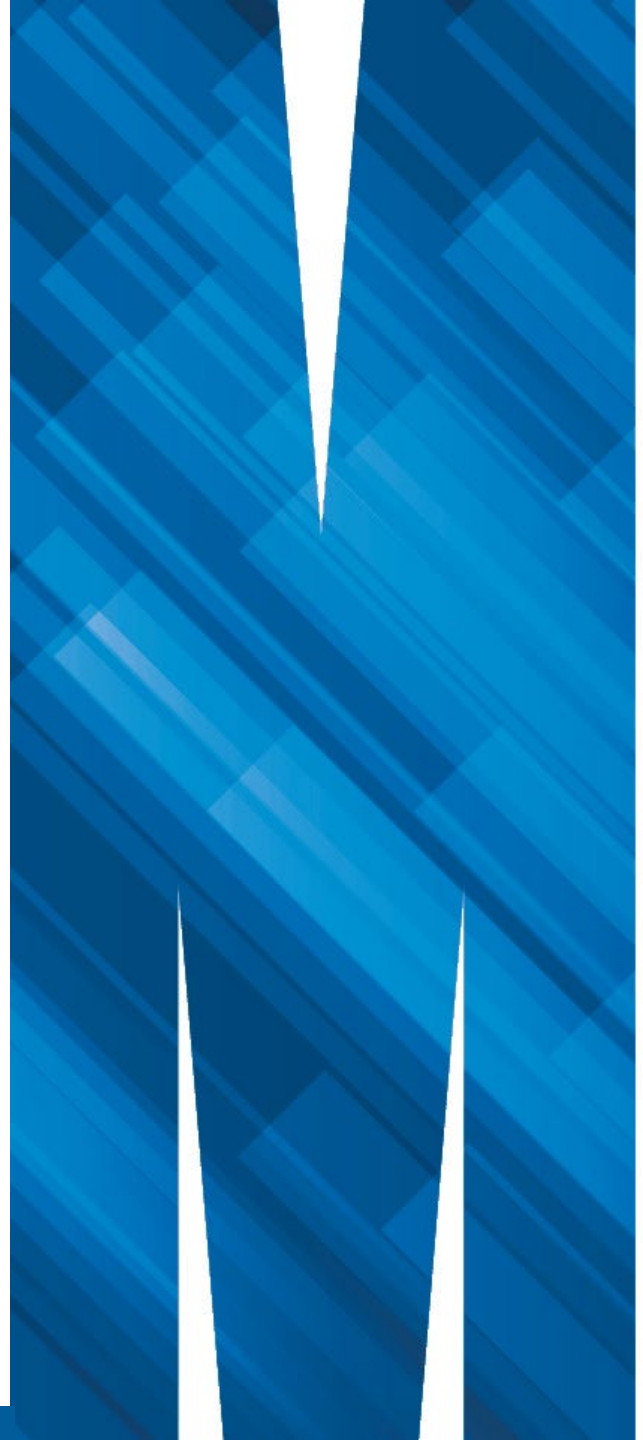
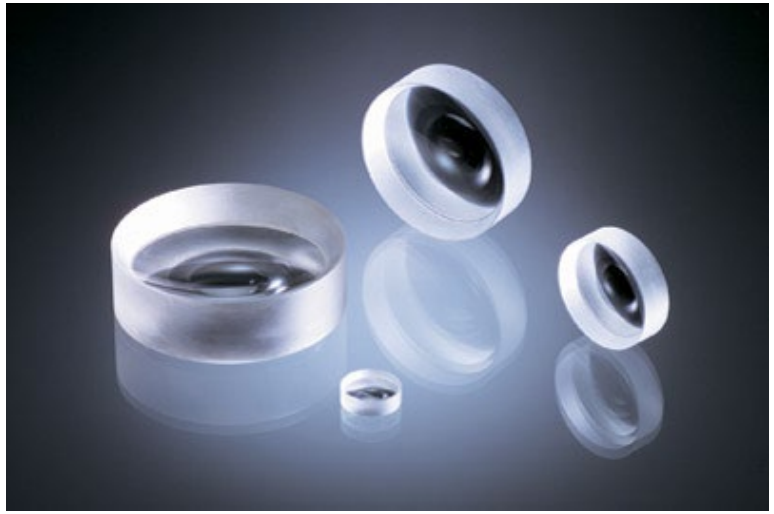
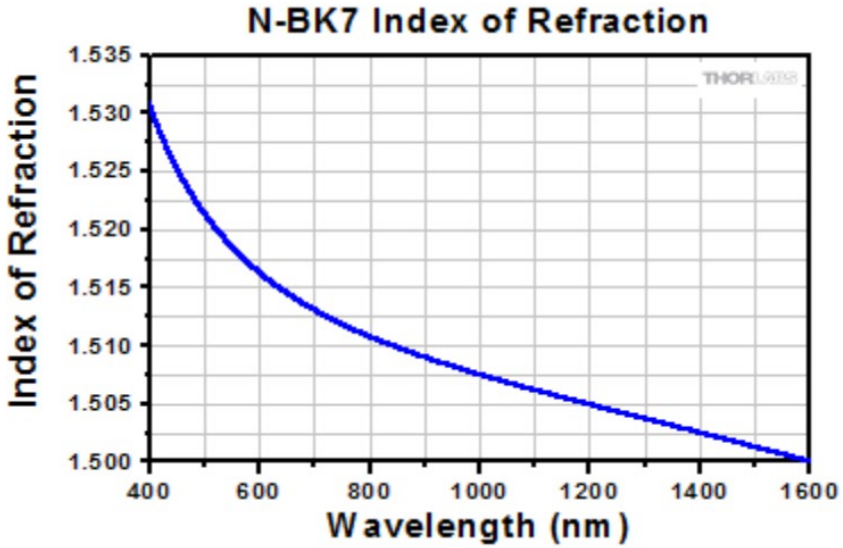
Design of a 3D achromatic metalens

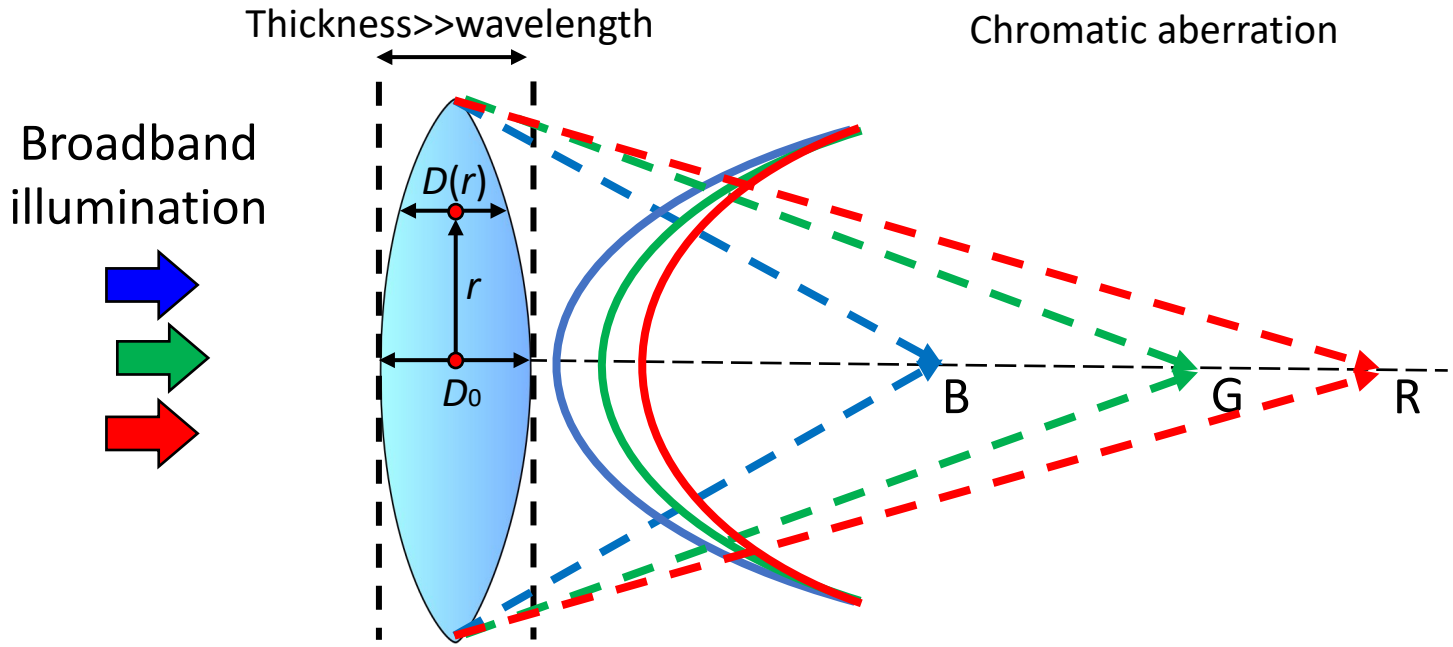


Chromatic aberration in a refractive lens



https://www.ealingcatalog.com/optics.html



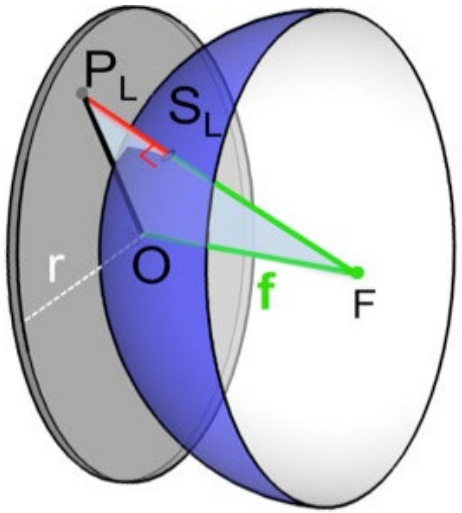


Phase function of a refractive lens: $\varphi(r,w) = \frac{w}{c} n_w D(r) + \frac{w}{c}[D_0 - D(r)]$

Phase shift of an off-axis position $D(r)$ with respect to the on-axis position (D_0) at frequency w :

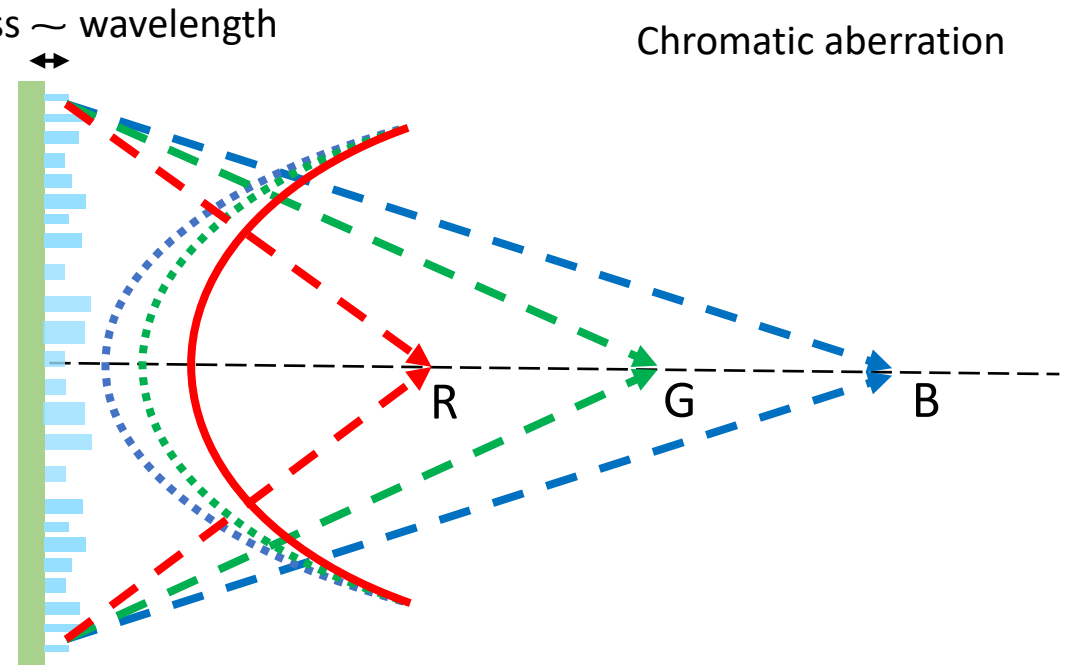
$$\Delta\varphi(r,w) = \frac{w}{c} n_w [D(r) - D_0] + \frac{w}{c}[D_0 - D(r)]$$
$$= \frac{w}{c}(n_w\text{-}1)[D(r) - D_0]$$

Chromatic aberration in a metalens



F. Aieta, et. al., *Nano Lett.* **12**, 4932 (2012).

Broadband illumination



Phase function of a diffractive metalens:

$$\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2+F^2}-F\right)$$

Taylor expansion up to first order at the minimum frequency ω_{min} is:

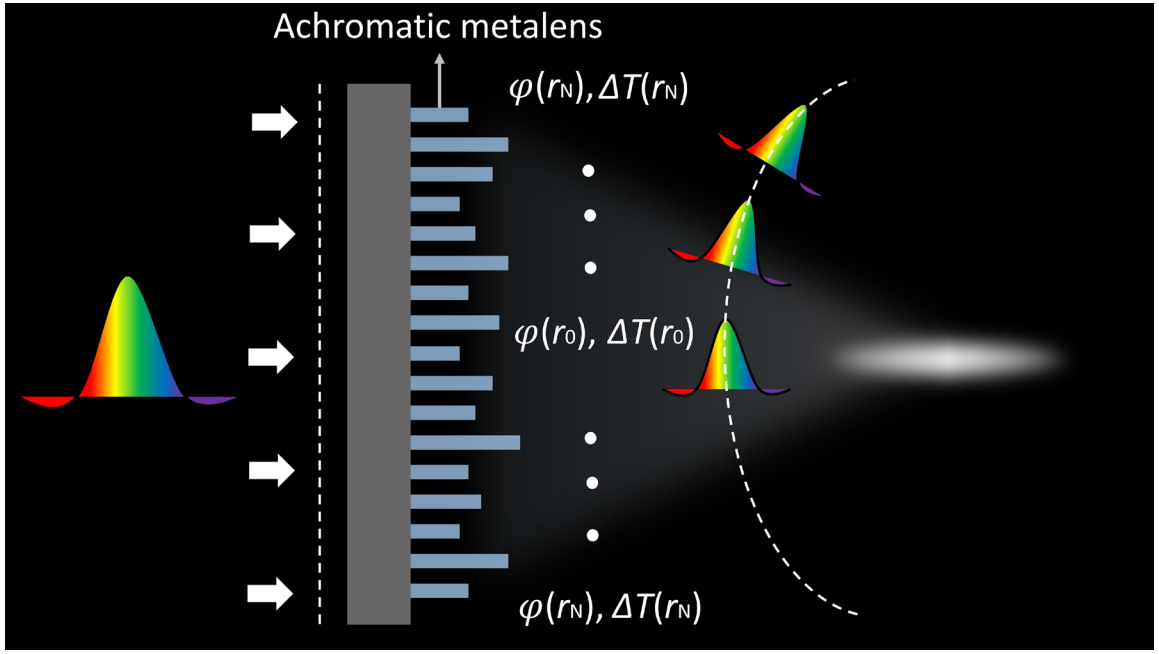
$$\varphi(r,\omega) = -\frac{\omega_{min}}{c}\left(\sqrt{r^2+f^2}-f\right) + \left.\frac{d\varphi}{d\omega}\right|_{\omega=\omega_{min}} (\omega-\omega_{min})$$

$$= -\frac{\omega_{min}}{c}\left(\sqrt{r^2+f^2}-f\right) - \frac{1}{c}\left(\sqrt{r^2+f^2}-f\right)(\omega-\omega_{min})$$

Group delay response (*r*-dependent) is:

$$\frac{d\varphi}{d\omega} = -\left(\frac{\sqrt{r^2+f^2}-f}{c}\right)$$

Time-bandwidth product of a 3D achromatic metalens



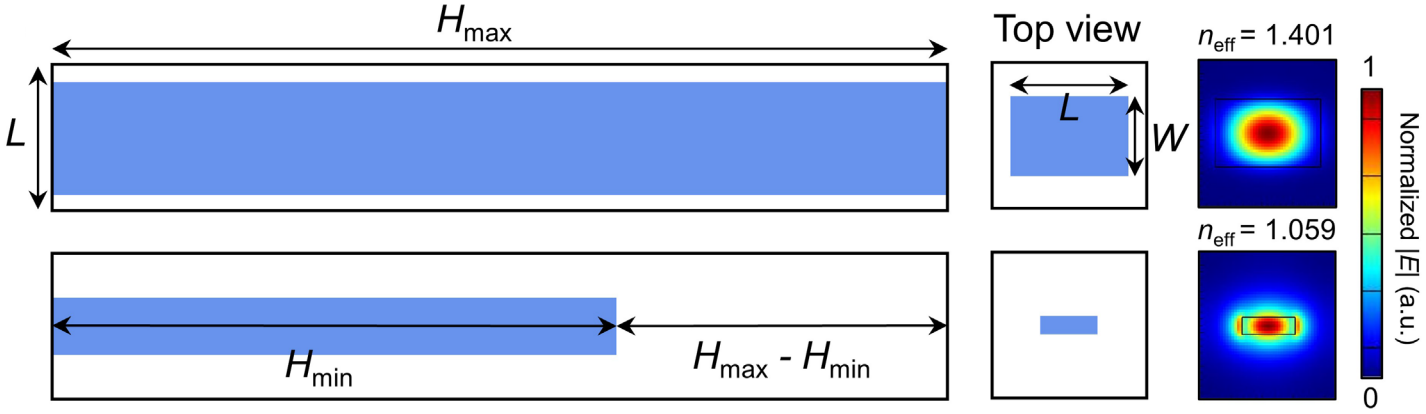
The upper bound of the time-bandwidth product κ for a waveguide-type metalens with a fixed height H:

$$\kappa = \frac{\omega_c}{c} H \cdot (n_{eff}^{max} - n_{eff}^{min})$$

The unleashed height degree of freedom of 3D meta-atoms allows an expanded κ:

$$\kappa = \frac{\omega_c}{c}\left(H_{max} n_{eff}^{max}\right) - \frac{\omega_c}{c}\left(H_{min} n_{eff}^{min} + (H_{max} - H_{min}) n_b\right)$$

$$= \frac{\omega_c}{c}(H_{max} \cdot \Delta n_{eff}^{max} - H_{min} \cdot \Delta n_{eff}^{min})$$



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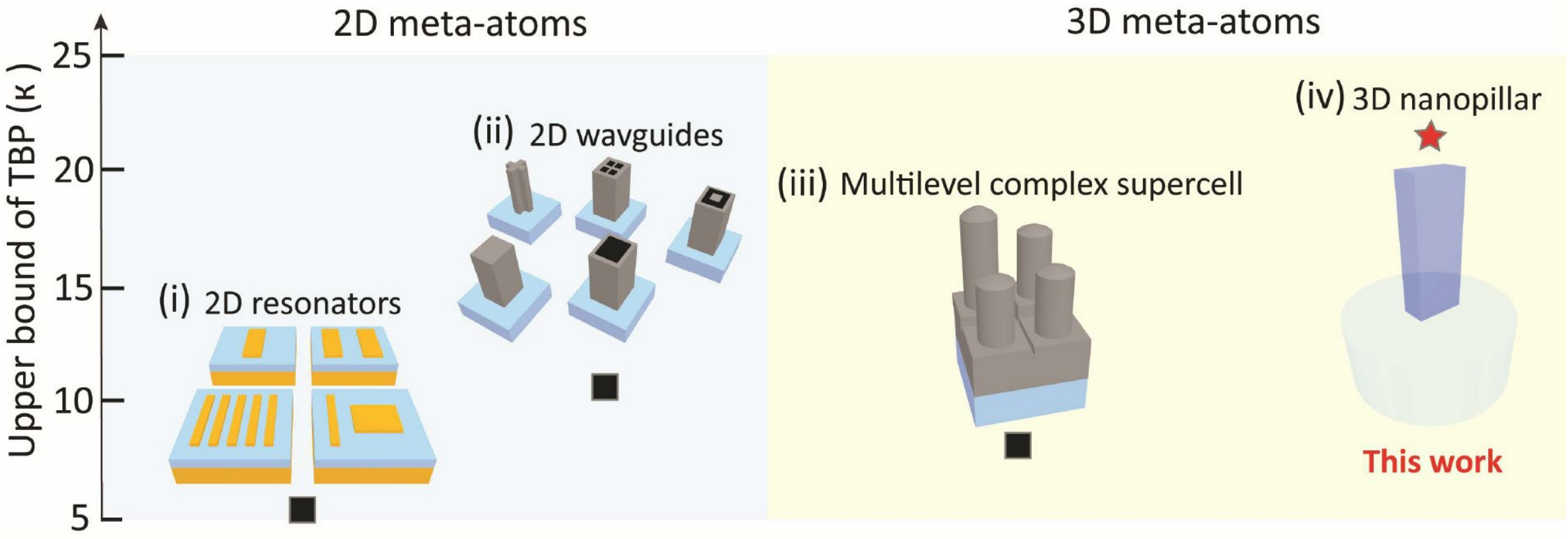
Time-bandwidth product of a 3D achromatic metalens



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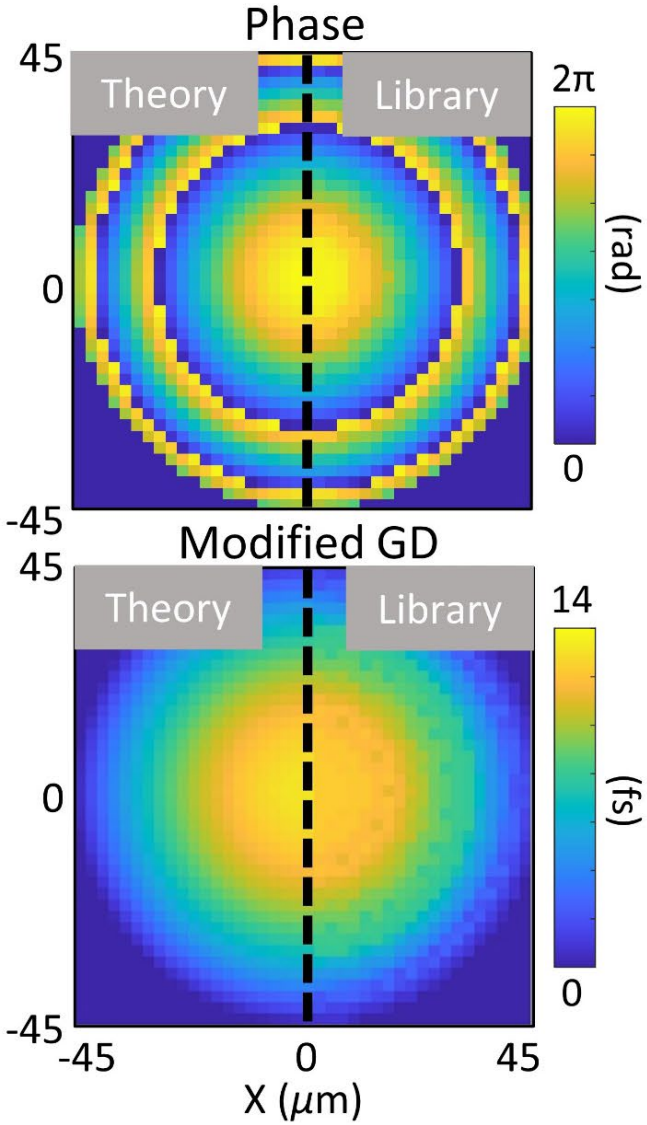
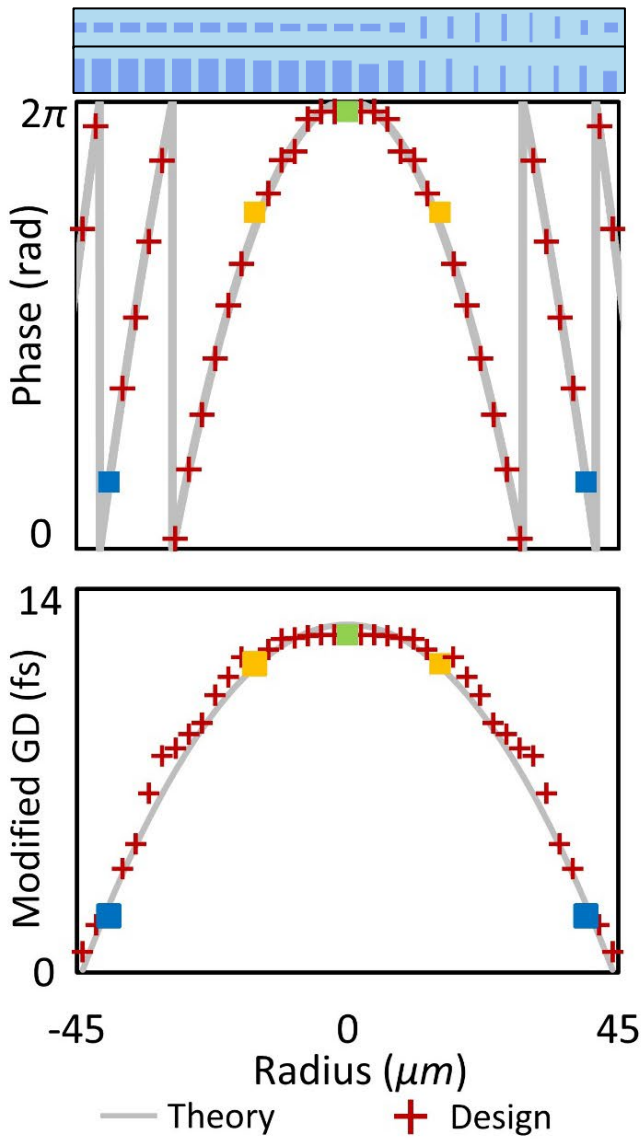
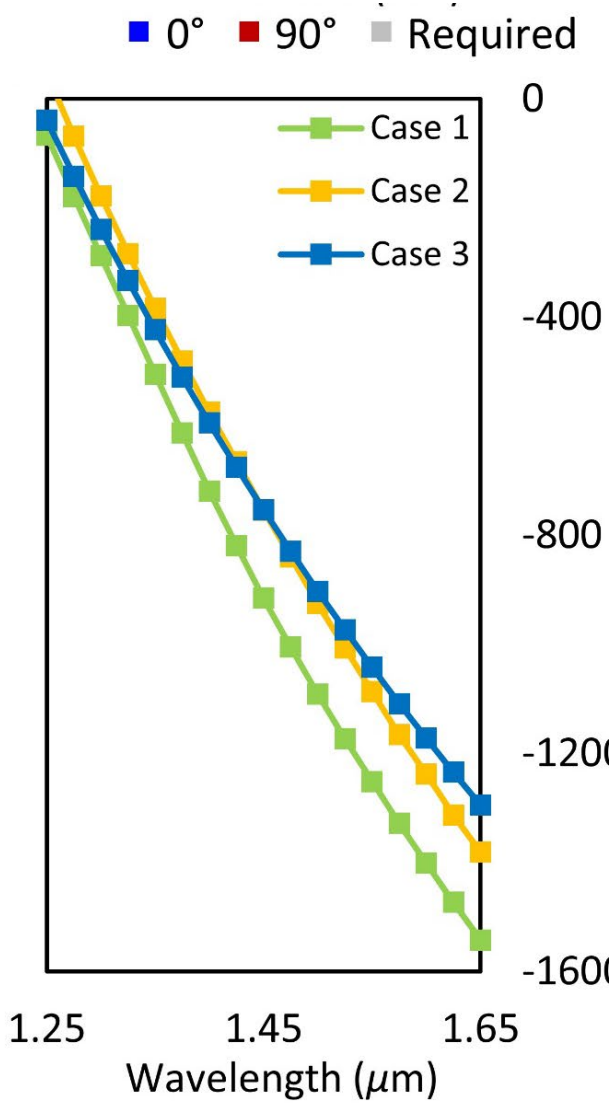
Design of a polarisation-insensitive achromatic metalens

H. Ren, J. Jang, C. Li, A. Aigner, M. Plidschun, J. Kim, J. Rho, M. A. Schmidt, and S. A. Maier, An achromatic metafiber for focusing and imaging across the entire telecommunication range, ***Nat. Commun.***, 13, 4183 (2022).







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Nanofabrication of a metafibre

3D laser printing – the beginning

OPTICS LETTERS / Vol. 22, No. 2 / January 15, 1997

Three-dimensional microfabrication with two-photon-absorbed photopolymerization

Shoji Maruo, Osamu Nakamura, and Satoshi Kawata

Department of Applied Physics, Osaka University, Suita, Osaka 565, Japan

Received October 1, 1996

We propose a method for three-dimensional microfabrication with photopolymerization stimulated by two-photon absorption with a pulsed infrared laser. An experimental system for the microfabrication has been developed with a Ti:sapphire laser whose oscillating wavelength and pulse width are 790 nm and 200 fs, respectively. The usefulness of the proposed method has been verified by fabrication of several kinds of microstructure by use of a resin consisting of photoinitiators, urethane acrylate monomers, and urethane acrylate oligomers. © 1997 Optical Society of America

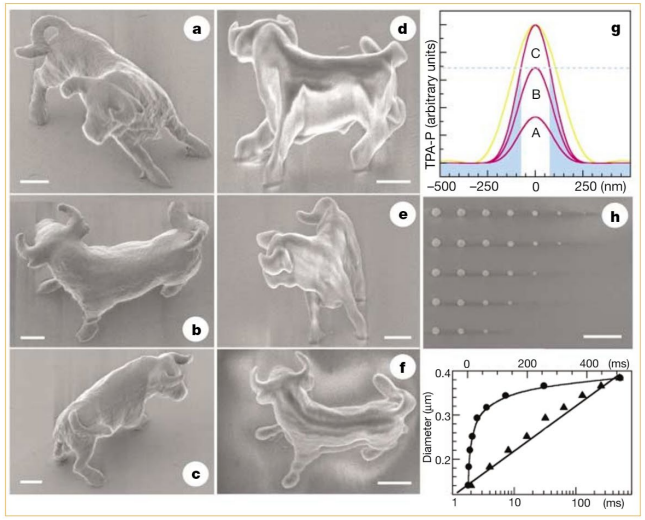
brief communications

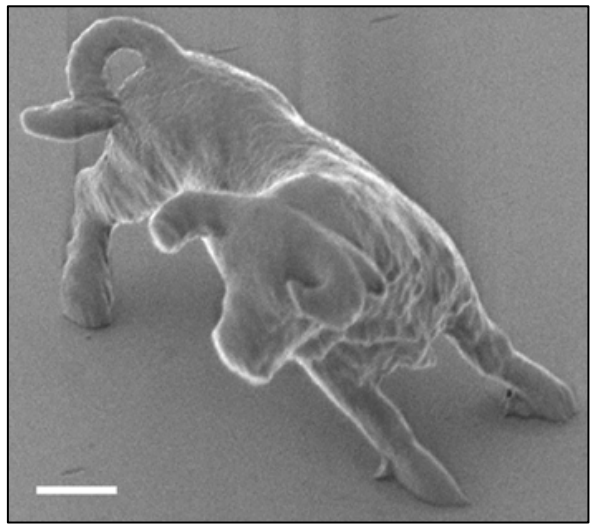
Finer features for functional microdevices

Micromachines can be created with higher resolution using two-photon absorption.

Compared with light or electron-beam lithography, the virtue of two-photon photopolymerization[1] as a tool for making microdevices lies in its three-dimensional capability, which has found application in photonic devices[2–4] and micromachines[1,5,6] with feature sizes close to the diffraction limit. Here we show that the diffraction limit can be exceeded by non-linear effects to give a subdiffraction-limit spatial resolution of 120 nanometres. This allows functional micromachines to be created and shifts the working wavelength of photonic and opto-electronic devices into the visible and near-infrared region.

Commercially available resin (SCR500; JSR, Japan), consisting of urethane acrylate monomers and oligomers as well as photo-initiators, is transparent to an infrared laser and allows it to penetrate deeply. The resin can be photopolymerized by using two-photon absorption (TPA)[7–9] to create three-dimensional structures. By pinpoint-scanning the laser focus according to pre-programmed patterns, designs can be faithfully replicated to matter structures.





10 micrometers long bull

Nature **412**, 697–698 (2001)

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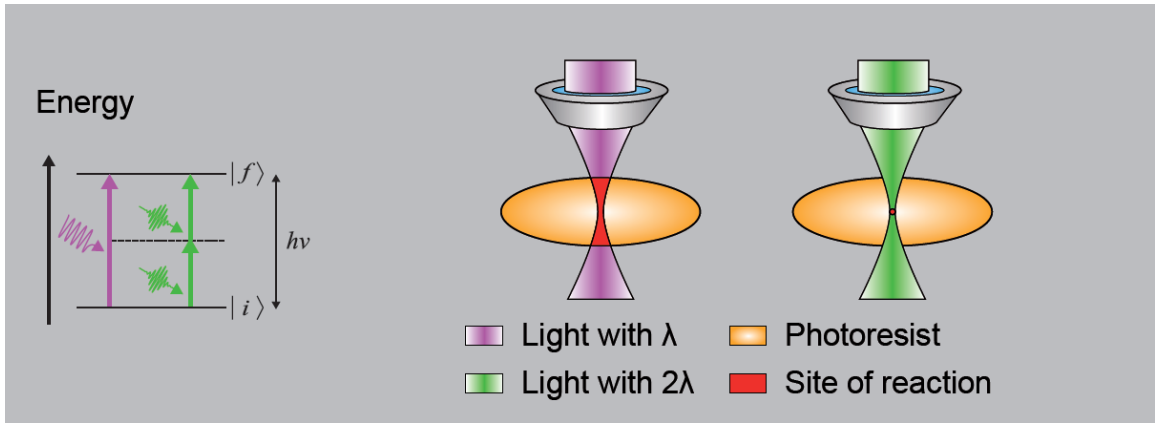
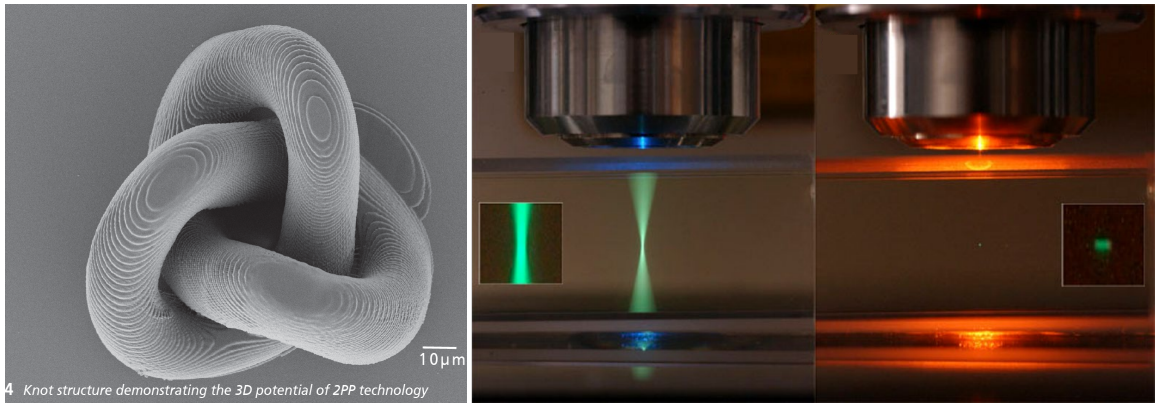
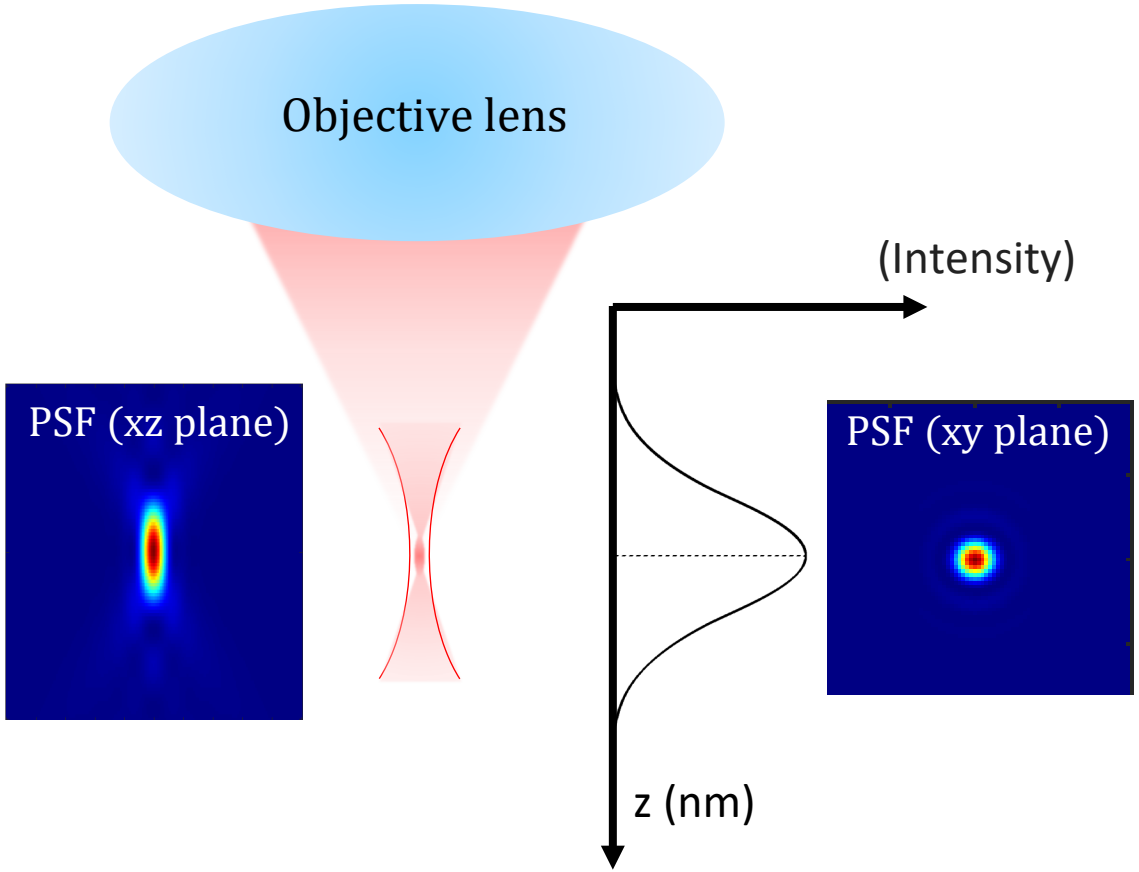
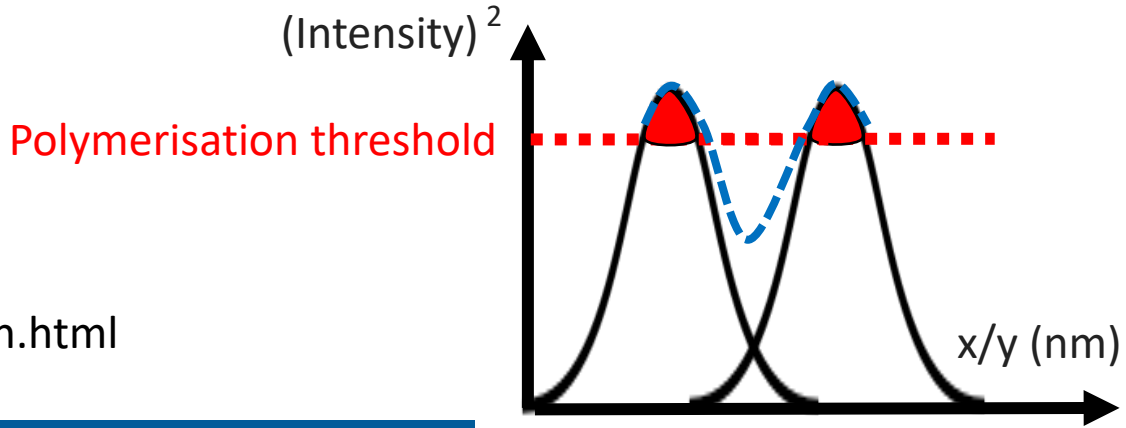
Two-photon polymerisation



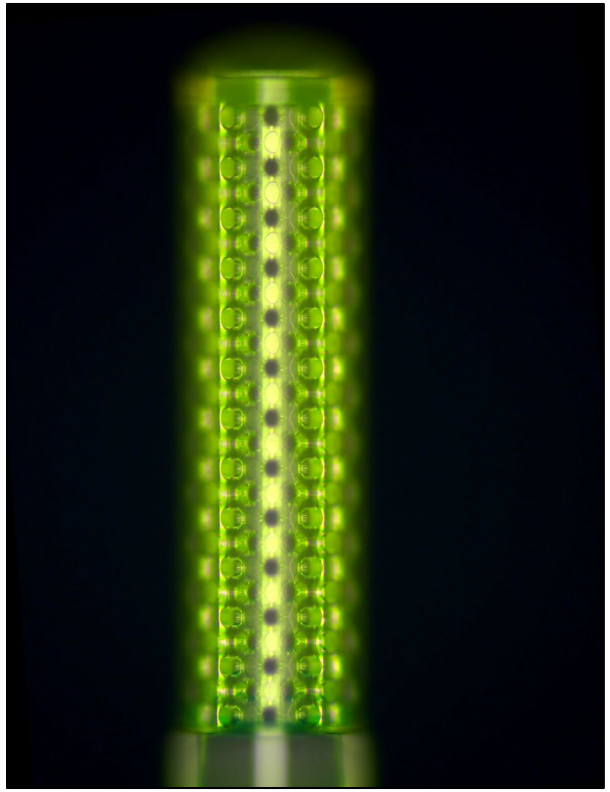


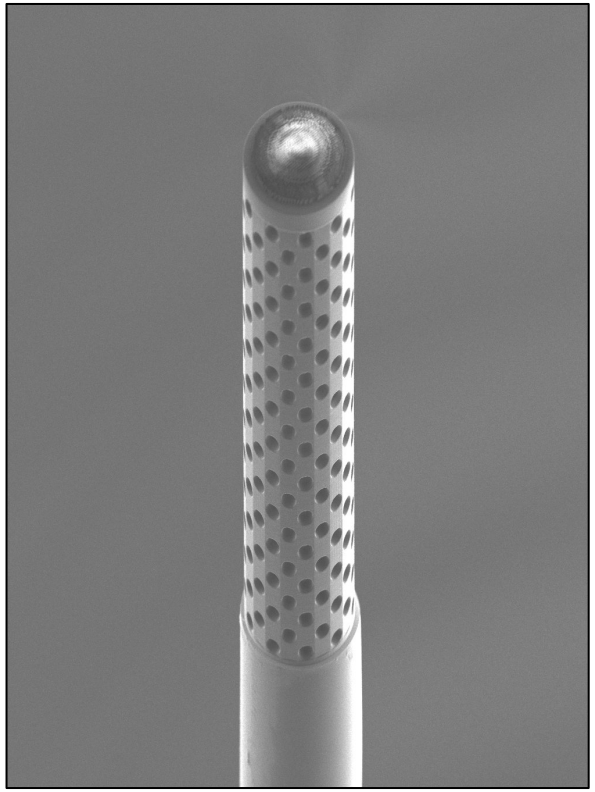


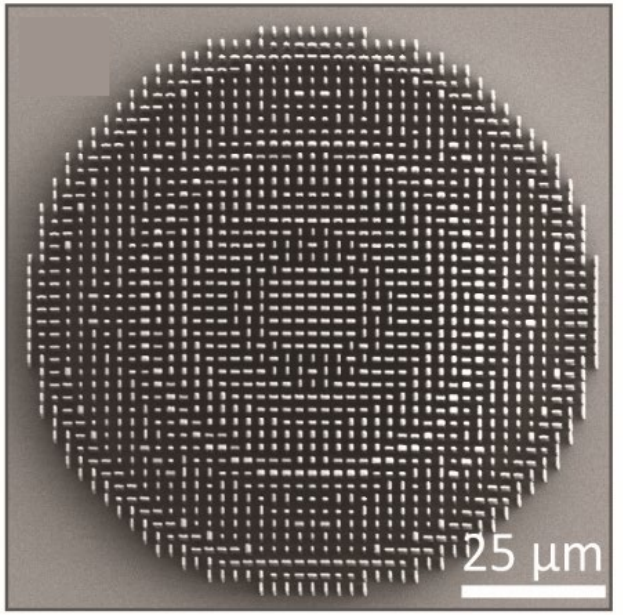


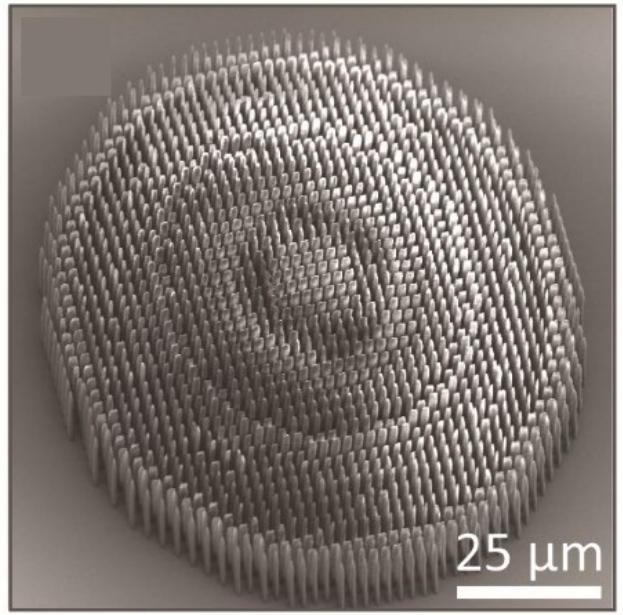
https://www.cesma.de/en/processing/two-photon-polymerization.html

A 3D laser-manufactured achromatic metafibre









H. Ren, J. Jang, C. Li, A. Aigner, M. Plidschun, J. Kim, J. Rho, M. A. Schmidt, and S. A. Maier, An achromatic metafiber for focusing and imaging across the entire telecommunication range, ***Nat. Commun.***, 13, 4183 (2022).

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An achromatic metafibre for focusing and imaging across the entire telecommunication range

Characterisation of the achromatic metafibre

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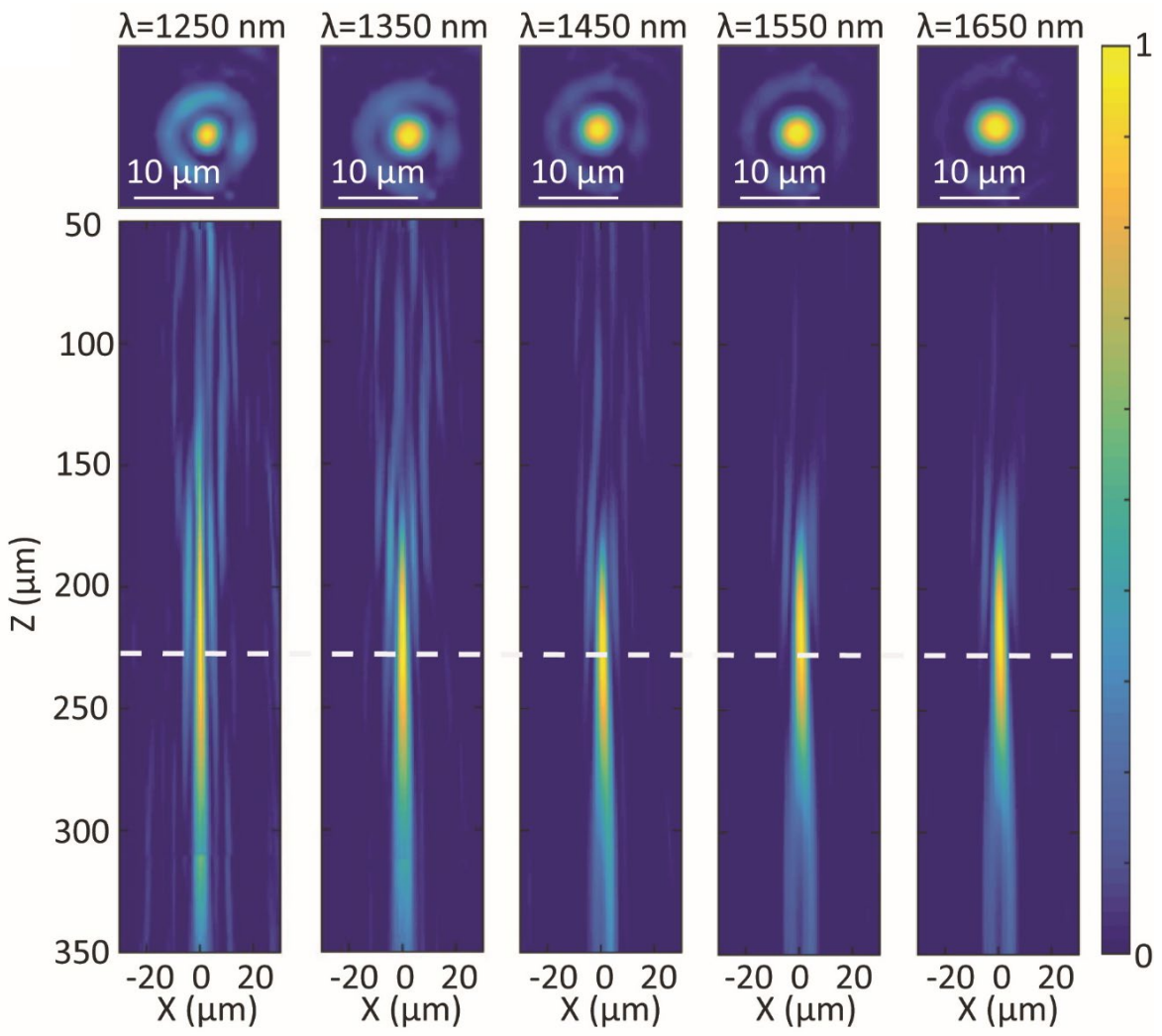
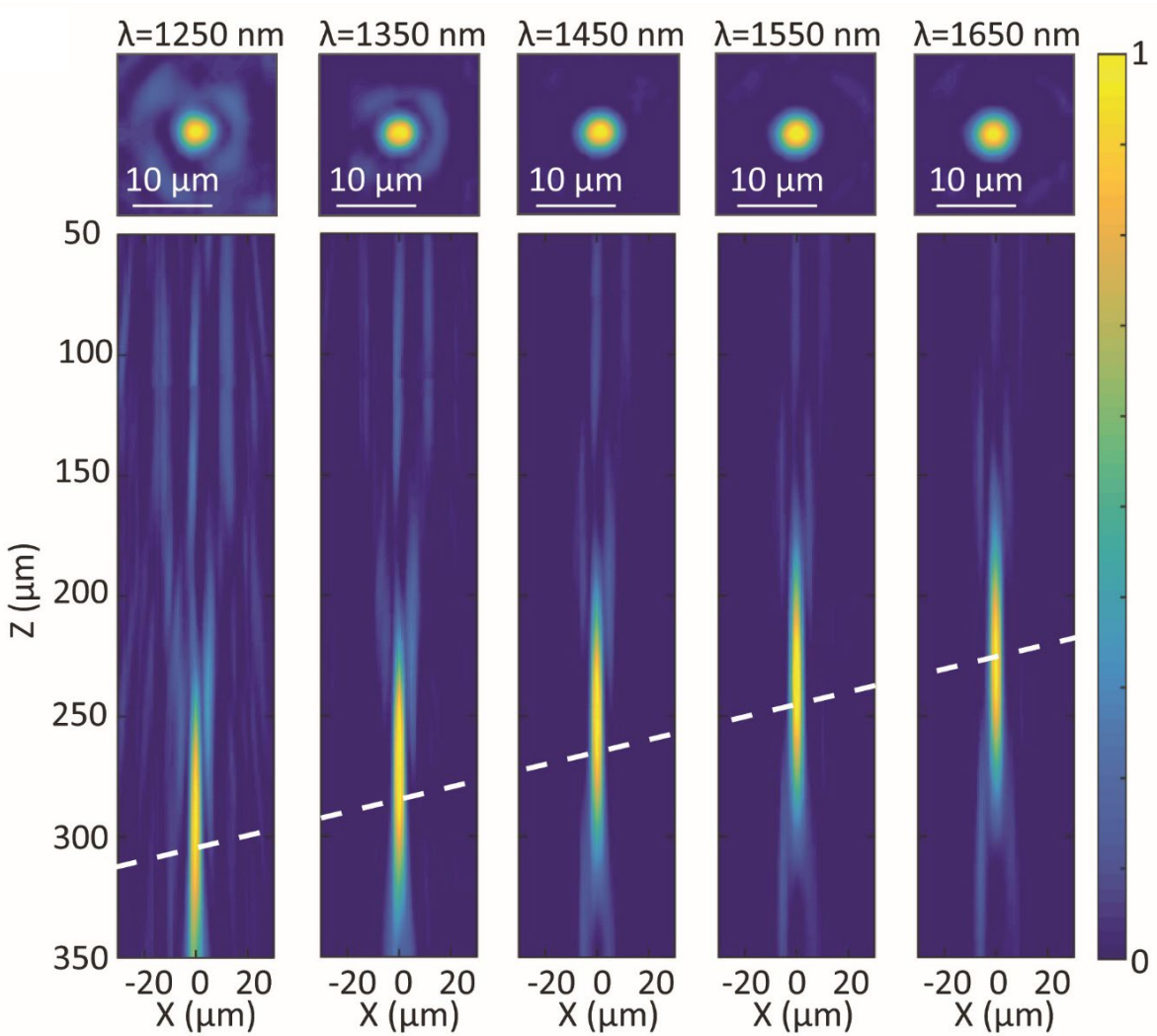
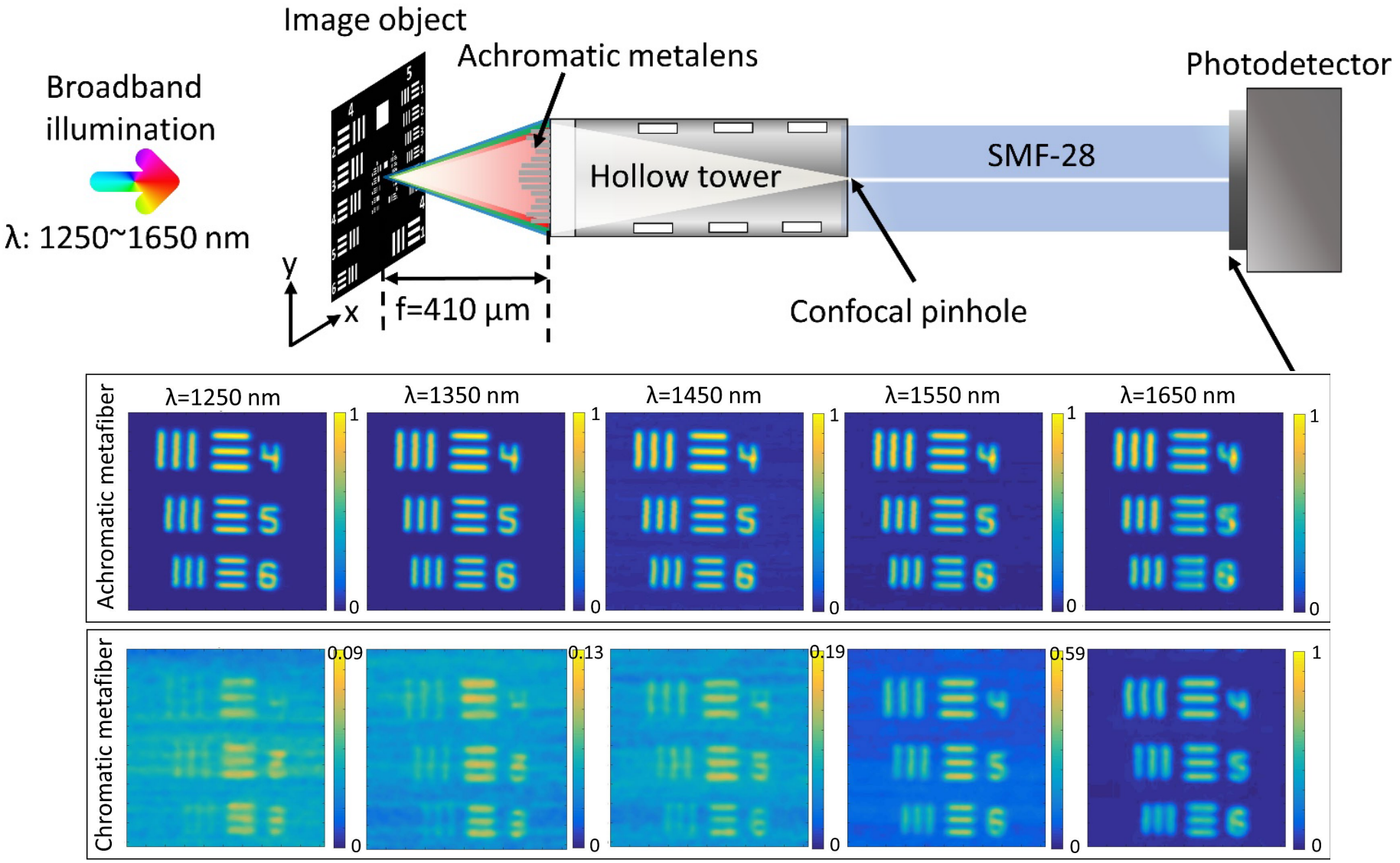
Achromatic metafibre



Chromatic metafibre



Achromatic metafibre imaging



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An achromatic metafiber for focusing and imaging across the entire telecommunication range

Haoran Ren[1,2,10✉], Jaehyuck Jang[3,10], Chenhao Li[2,10], Andreas Aigner[2], Malte Plidschun[4,5], Jisoo Kim[4,5], Junsuk Rho[3,6,7✉], Markus A. Schmidt[4,5,8✉] & Stefan A. Maier[1,2,9✉]

Dispersion engineering is essential to the performance of most modern optical systems including fiber-optic devices. Even though the chromatic dispersion of a meter-scale single-mode fiber used for endoscopic applications is negligible, optical lenses located on the fiber end face for optical focusing and imaging suffer from strong chromatic aberration. Here we present the design and nanoprinting of a 3D achromatic diffractive metalens on the end face of a single-mode fiber, capable of performing achromatic and polarization-insensitive focusing across the entire near-infrared telecommunication wavelength band ranging from 1.25 to 1.65 μm. This represents the whole single-mode domain of commercially used fibers. The unlocked height degree of freedom in a 3D nanopillar meta-atom largely increases the upper bound of the time-bandwidth product of an achromatic metalens up to 21.34, leading to a wide group delay modulation range spanning from −8 to 14 fs. Furthermore, we demonstrate the use of our compact and flexible achromatic metafiber for fiber-optic confocal imaging, capable of creating in-focus sharp images under broadband light illumination. These results may unleash the full potential of fiber meta-optics for widespread applications including hyperspectral endoscopic imaging, femtosecond laser-assisted treatment, deep tissue imaging, wavelength-multiplexing fiber-optic communications, fiber sensing, and fiber lasers.

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