Nonlinear interaction of vortices to generate deep sub-wavelength acoustical vortex beams.

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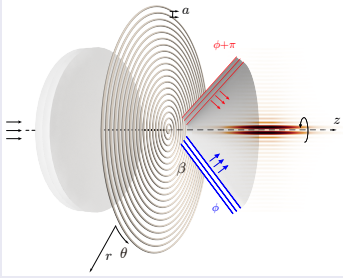
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Outline

1. Introduction
   - Vortices: Definition, applications and generation
   - Goal of the work
   - Main ingredients
2. Experimental set-up
   - Demodulation effect
3. Results: Nonlinear vortex generation
   - Sagital field cross-sections
   - Transvers field cross-sections
   - Subwavelenght size
4. Conclusions

Vortex beams are characterized by a collimated wavefront with a phase dependence of the type $e^{il\phi}$, with ϕ the azimuthal angle and l the topological charge, respectively. At the principal axis of the beam, the field exhibits a phase singularity and the field is null.



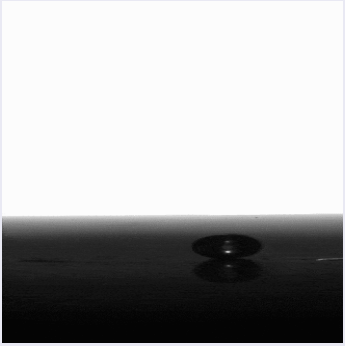
N. Jiménez PRE 94, 053004 (2016)

Particle trapping



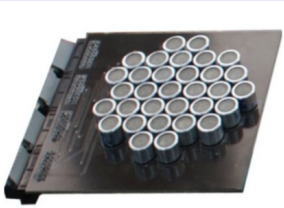
D. Baresch, PRL, 116, 024301, (2016)
J. Wu, JASA, 89, 2140 (1991)
A. Mazo, PRL, 120, 044301, (2018)

Manipulation



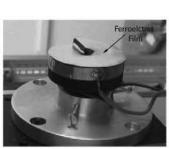
D. Baresch, PRL, 116, 024301, (2016)
Z. Gong PRApplied, 12, 024045 (2019)
C. R. Courtney APL, 102, 123508 (2013).

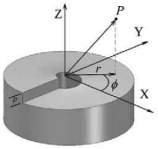
Phase arrays



J.-L. Thomas, PRL, 91, 244302 (2003)
R. Marchiano PRE, 71, 066616 (2005)
J. F. Pazos-Ospina, JASA, 142, 61 (2017)

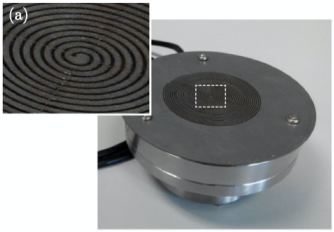
Helical surface





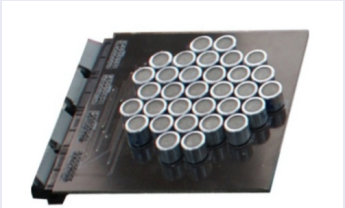
B. T. Hefner JASA 106, 3313 (1999)
J. L. Ealo, IEEE 58, 1651 (2011)

Spiral grattings



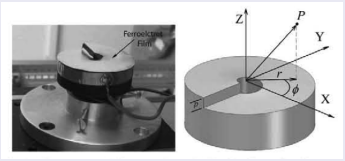
N. Jiménez PRE 94, 053004 (2016)
T. Wang APL 109, 123506 (2016)
N. Jiménez, APL 112, 204101 (2018)

Phase arrays



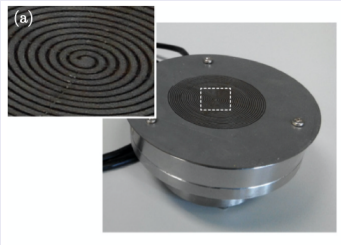
J.-L. Thomas, PRL, 91, 244302 (2003)
R. Marchiano PRE, 71, 066616 (2005)
J. F. Pazos-Ospina, JASA, 142, 61 (2017)

Helical surface



B. T. Hefner JASA 106, 3313 (1999)
J. L. Ealo, IEEE 58, 1651 (2011)

Spiral grattings



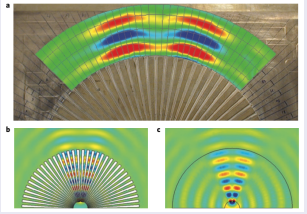
N. Jiménez PRE 94, 053004 (2016)
T. Wang APL 109, 123506 (2016)
N. Jiménez, APL 112, 204101 (2018)

Size vs. Rayleigh distance

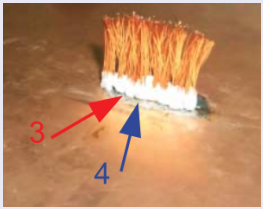
However, in all these configurations the natural diffraction of the wavefront limits the size of the vortex, being the minimum size only reached for distances smaller than the Rayleigh diffraction length of the source.
This distance is given by S/λ where S is the surface of a circular-aperture source.

Is it possible to synthesize a vortex beam of sub-wavelength size at a distance beyond Rayleigh diffraction length?

Restoring the evanescent components of a field.



J. Li, Nat. Mater. 8, 931 (2009)
J. B. Pendry, PRL 85, 3966 (2000)



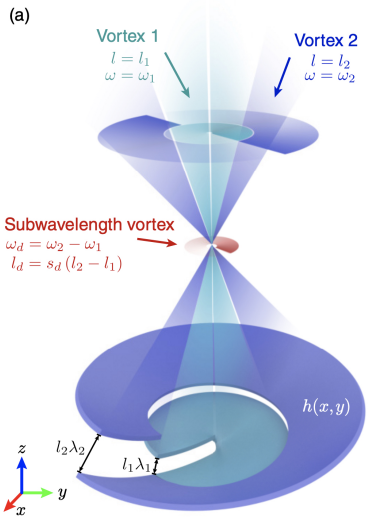
G. Lerosey Science 315, 1120 (2007)
N. Fang Science 308, 534 (2005)

Restrictions to near-field distances!

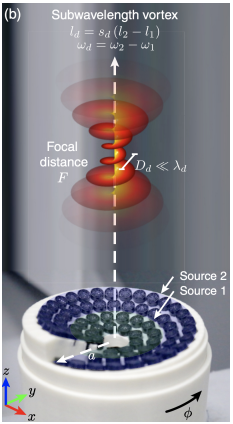
Goal of the work

- Using the nonlinear mixing of two confocal, high-frequency and detuned vortex beams of different topological charges.
- The natural self-demodulation phenomenon in air, will help to generate a focused vortex beam of tuned topological charge whose distance between magnitude maxima will be sub-wavelength at a distance larger than the Rayleigh diffraction length.

- Two helical profiles are designed to generate a focused beam at a focal point, $F = 100$ mm.
- The curvature is chosen to produce at focus a difference of time of flight equal to $\Delta t_n = l_n \phi / \omega_n$, where l_n is the topological charge of the n-th primary vortex beam, ω_n the angular frequency and ϕ the azimuthal coordinate (n=1,2).
  - $l_1 = 1$, $l_2 = 2$.
  - $\omega_1 = 40$ kHz, $\omega_2 = 41$ kHz.
- Both beams interact and due to material and advective nonlinearity, wave mixing occurs during propagation.

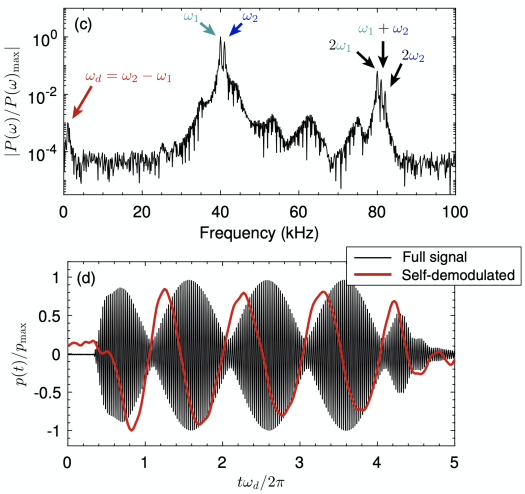


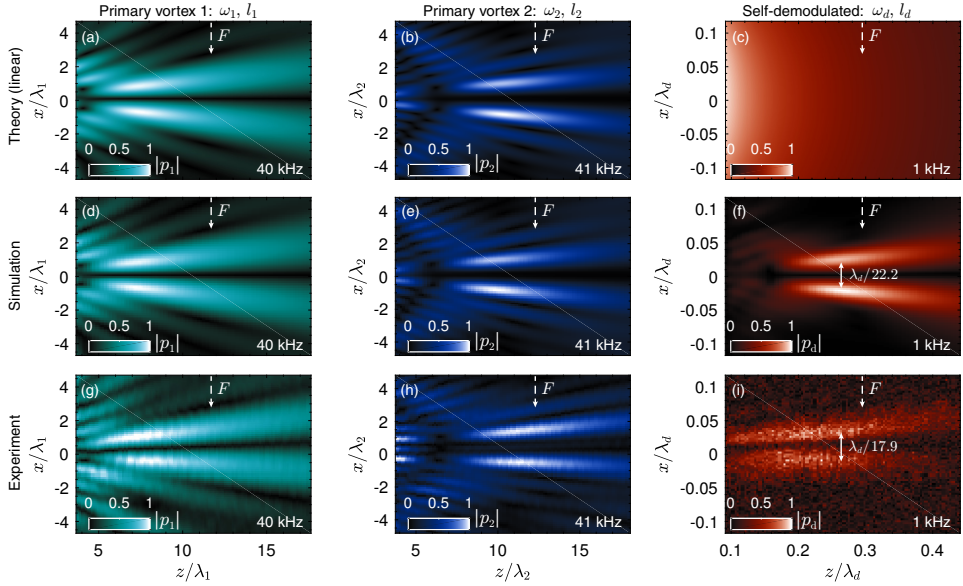
- A device was manufactured by disposing 10-mm diameter ultrasound emitters operating in air over two different helical surfaces.
- As homogeneous acoustic media lack of strong dispersion, phase-matching holds during nonlinear propagation and harmonic generation processes are cumulative with distance.
- It is expected that the locally-generated self-demodulated mode presents a field spatial distribution similar to those of the primary beams
- The phase of the self-demodulated beam depends on the spatio-temporal interference of the two vortex beams, which is linked to their topological charges. This results in a self-demodulated beam with a phase factor $\exp(il_d\phi)$ where the topological charge of the self-demodulated beam is $l_d = s_d(l_2 - l_1)$, where $s_d = \text{sign}(\omega_2 - \omega_1)$.

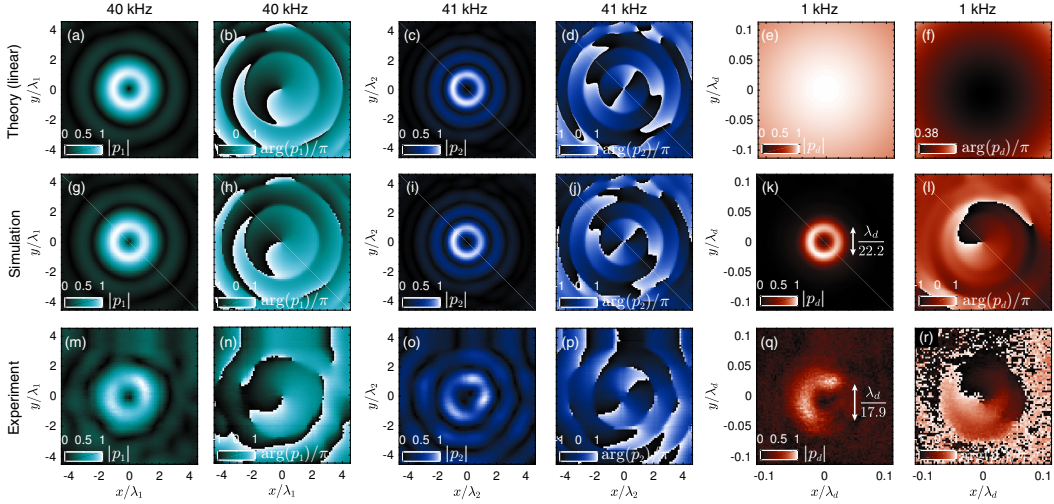


To synthesize a sub-wavelength vortex by self-demodulation, the primary beams should present different topological charges and frequencies and their field distribution must overlap in space.

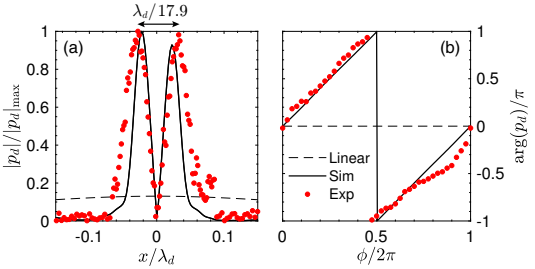
- The maximum pressure amplitude measured was 16.1 Pa (a sound pressure level of 118.1 dB referenced at 20 μPa), enough to trigger weak nonlinear effects.
- Higher and difference-frequency harmonics arise as arithmetical combinations of the fundamental waves of both beams.
- In addition to higher harmonics, a difference-frequency mode of frequency $\omega_d = \omega_2 - \omega_1$ was generated due to the nonlinear self-demodulation of the beating wavefront.




Primary vortex 1: ω_1, l_1
Primary vortex 2: ω_2, l_2
Self-demodulated: ω_d, l_d
Theory (linear)
Simulation
Experiment
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
F
$|p_1|$
$|p_2|$
$|p_d|$
40 kHz
41 kHz
1 kHz
$\lambda_d/22.2$
$\lambda_d/17.9$
x/λ_1
x/λ_2
x/λ_d
z/λ_1
z/λ_2
z/λ_d


40 kHz
40 kHz
41 kHz
41 kHz
1 kHz
1 kHz
Theory (linear)
Simulation
Experiment
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
(p)
(q)
(r)
$|p_1|$
$\arg(p_1)/\pi$
$|p_2|$
$\arg(p_2)/\pi$
$|p_d|$
$\arg(p_d)/\pi$
$\frac{\lambda_d}{22.2}$
$\frac{\lambda_d}{17.9}$
y/λ_1
x/λ_1
y/λ_2
x/λ_2
y/λ_d
x/λ_d

- The width of the vortex, D_d, is 17.9 times smaller than the wavelength in the experimental observations ($D_d = \lambda_d/22.2$ in simulations).
- The measurement distance is 2.8 times the Rayleigh diffraction length for the self-demodulated mode.
- The field at the axis ($x = 0$) becomes null due to the phase singularity.
- The phase of the beam along the azimuthal coordinate ϕ agrees with a linear profile of $(l_2 - l_1)\phi = l_d\phi$, demonstrating the topological charge conservation during nonlinear mixing.



Thank you for your attention

- "Juan de la Cierva - Incorporació" IJC2018-037897-I and PID2019-111436RB-C22, by the Agència Valenciana de la Innovació through grant IN- NVA1/2020/92
- This work has been funded by the HYPERMETA Project funded by Pays Région de la Loire.
- This work is based upon work from COST Action DENORMS - CA15125, supported by COST (European Cooperation in Science and Technology).

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