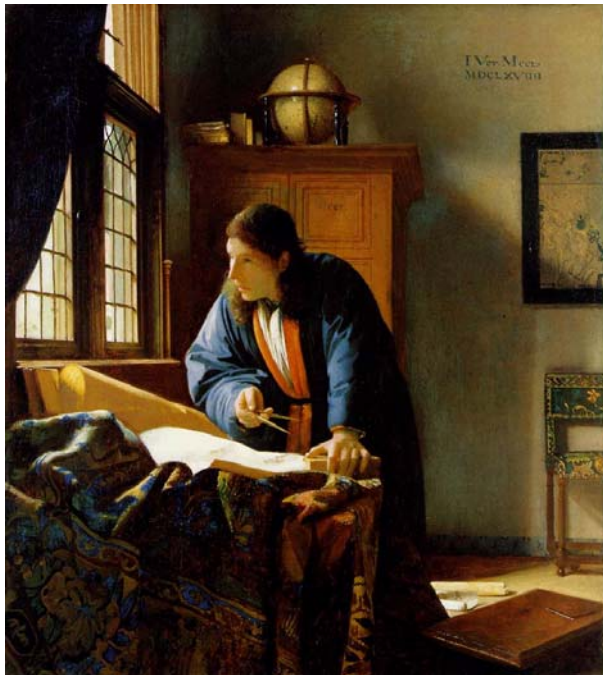


Día Virtual de la Comunidad de Enseñanza de las Ciencias

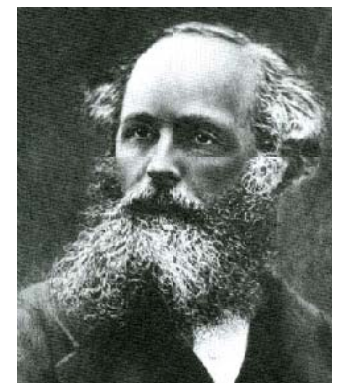
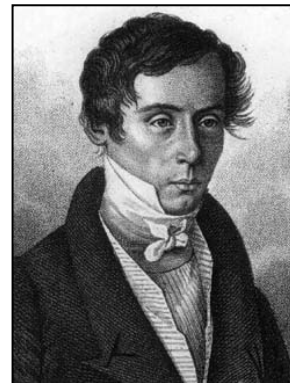


Luz en acción: Buscando la difracción cero.

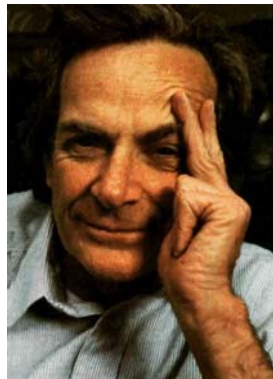
Julio C. Gutiérrez-Vega

Monterrey, N.L., 24 de noviembre de 2010

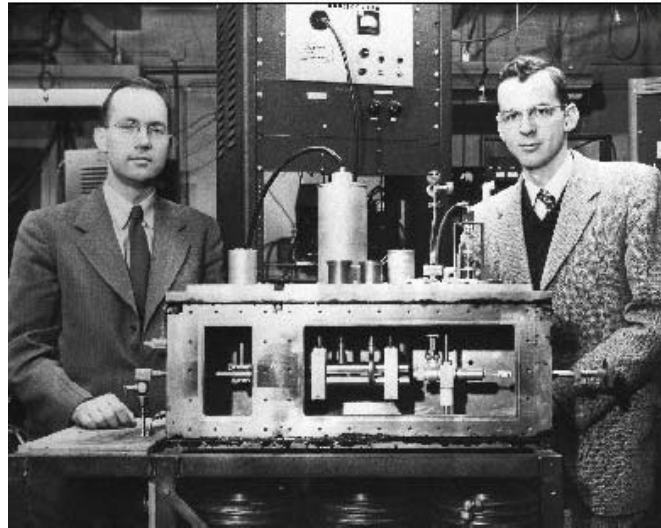
3000 años investigando la luz...



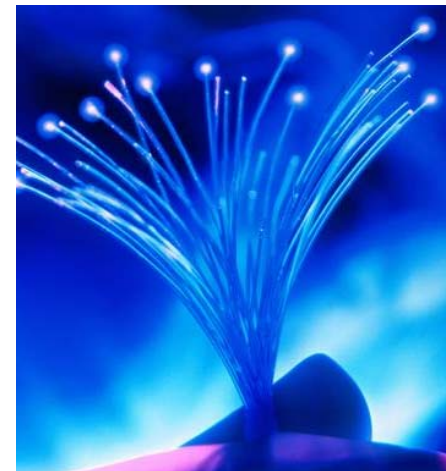
3000 años investigando la luz...



Invención del láser (1960)



Los **láseres** revolucionaron la ciencia y tecnología





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TITAN

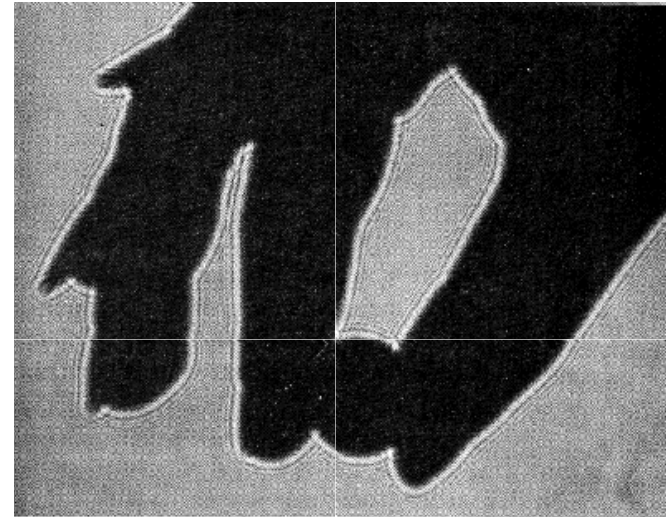


Star Wars © 2010 Lucasfilm Ltd. & TM All Rights Reserved. Used under authorisation.

Concepto de difracción

Según la Real Academia Española:

Difracción: Desviación de los rayos luminosos cuando pasan por un cuerpo opaco o por una abertura de diámetro menor o igual que la longitud de onda.



Según la Encyclopedia Britannica:

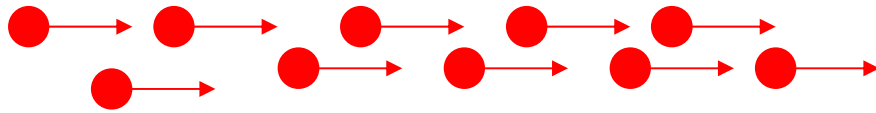
Diffraction: Spreading of waves around obstacles. When a beam of light falls on the edge of an object, it is bent slightly by the contact and causes a blur at the edge of the shadow of the object.



1694 Teoría corpuscular de Newton

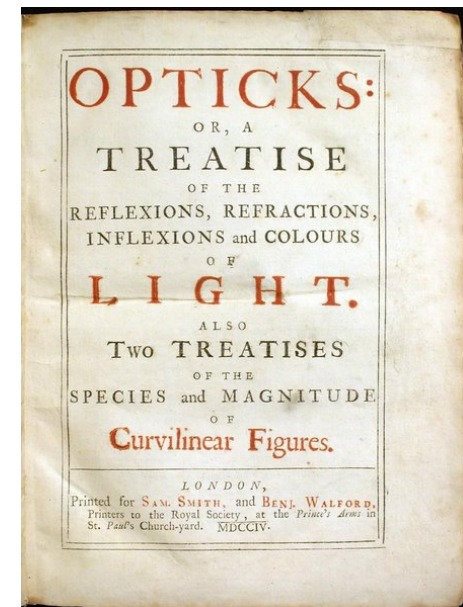
En 1694 Isaac Newton escribió:

"Nunca se ha sabido que la luz siga caminos torcidos o se doble hacia la sombra. Las partículas de la luz viajan siempre en línea recta"



Con esta teoría Newton buscó explicar:

La existencia de las sombras
La reflexión y refracción



1695 Teoría ondulatoria de Huygens

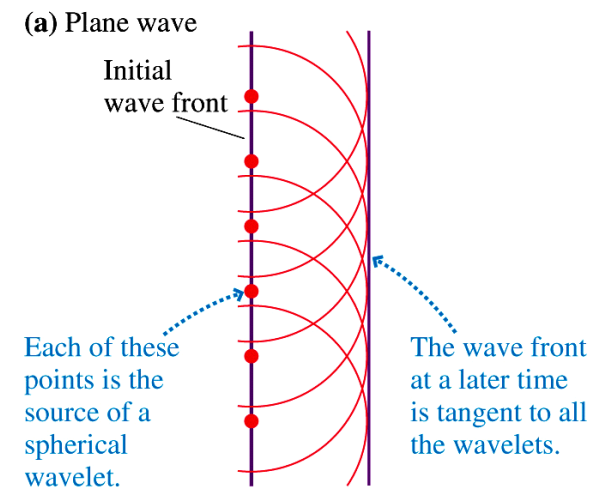
En 1695 **Christian Huygens** propuso el principio que ahora lleva su nombre como una manera geométrica de describir la luz.

Huygens argumentó que la luz se comportaba como una especie de onda.

Principio de Huygens:

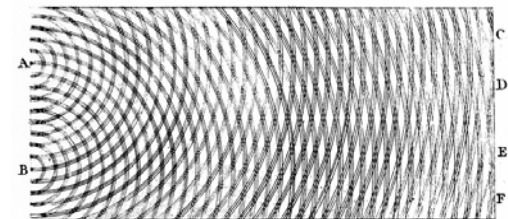
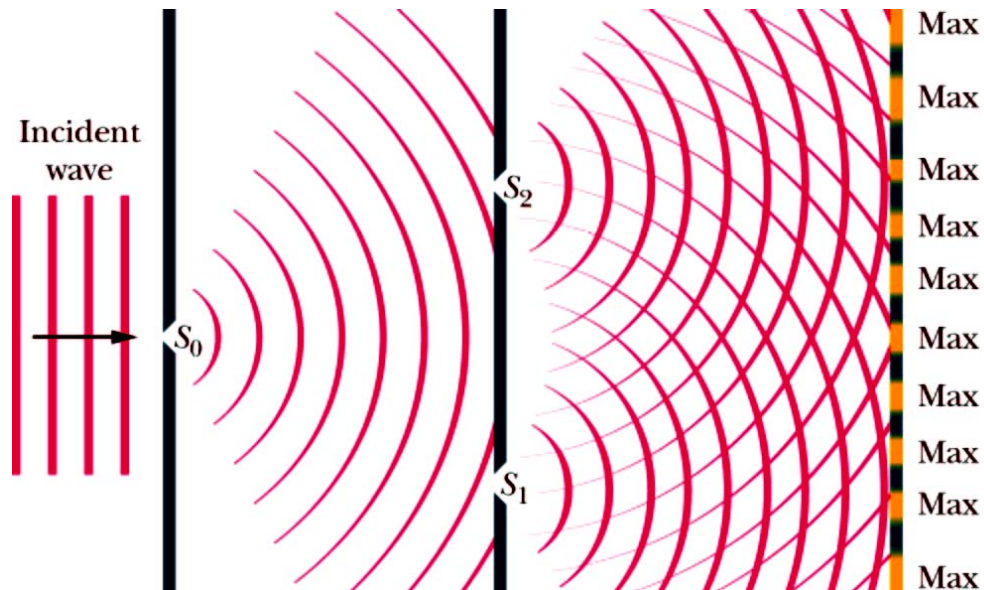
Consideremos un perfil de luz:

- 1) Cada punto del frente de onda es la fuente de una nueva onda esférica secundaria que se propaga a la velocidad inicial.
- 2) En un punto posterior del tiempo, el nuevo frente de onda en la superficie envolvente a todos las ondas secundarias



1803 El experimento de Young

En 1803 Thomas Young hizo su famoso experimento observando interferencia a partir de dos rendijas separadas una distancia muy pequeña. Para explicar este fenómeno, **él concluyó que la luz debe propagarse como ondas.**



1818 Teoría ondulatoria de la luz de Fresnel

En **1818**, **Fresnel** publicó un tratado donde da una descripción matemática de la luz usando el concepto de onda, contrario a la teoría corpuscular de Newton.

Poisson, quien era muy crítico de la teoría ondulatoria de la luz, usó la teoría de Fresnel para hacer la predicción (aparentemente absurda) de que detrás de una obstrucción circular debía aparecer un punto brillante de luz.

Arago demostró experimentalmente la existencia de lo que ahora se conoce como el punto de Poisson.

Con esta teoría Fresnel explicó:

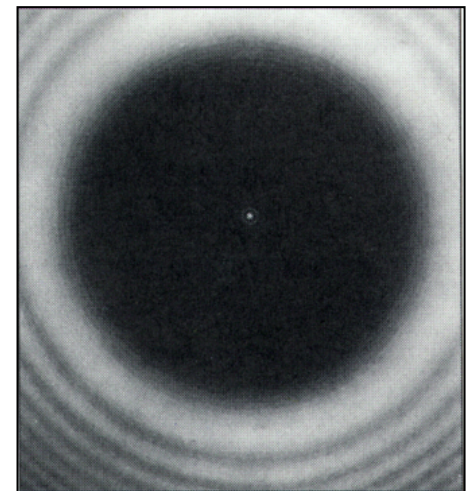
La existencia de las sombras

La reflexión y refracción

La interferencia

La difracción

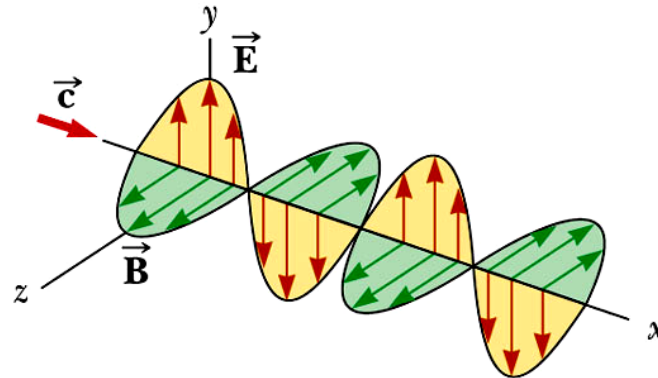
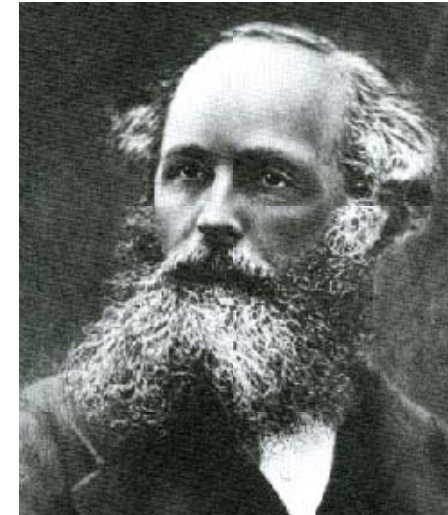
La birefringencia



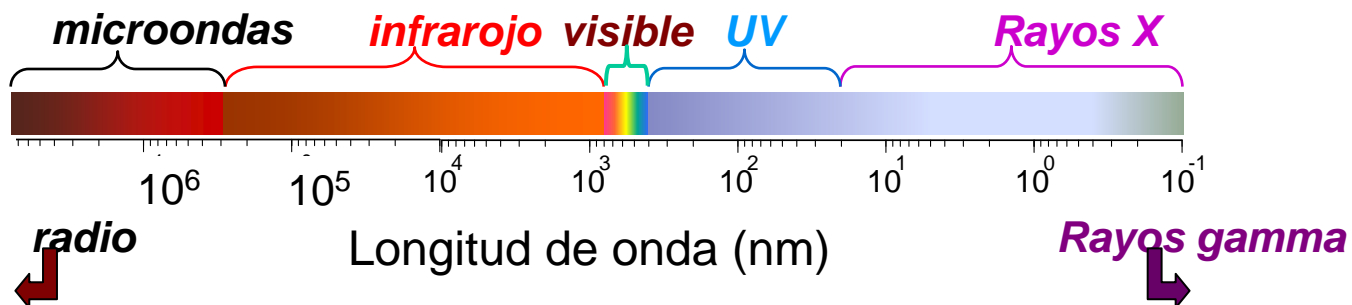
1865 La teoría vectorial de la luz de Maxwell

En 1865 Maxwell publicó la formulación vectorial del campo electromagnético.

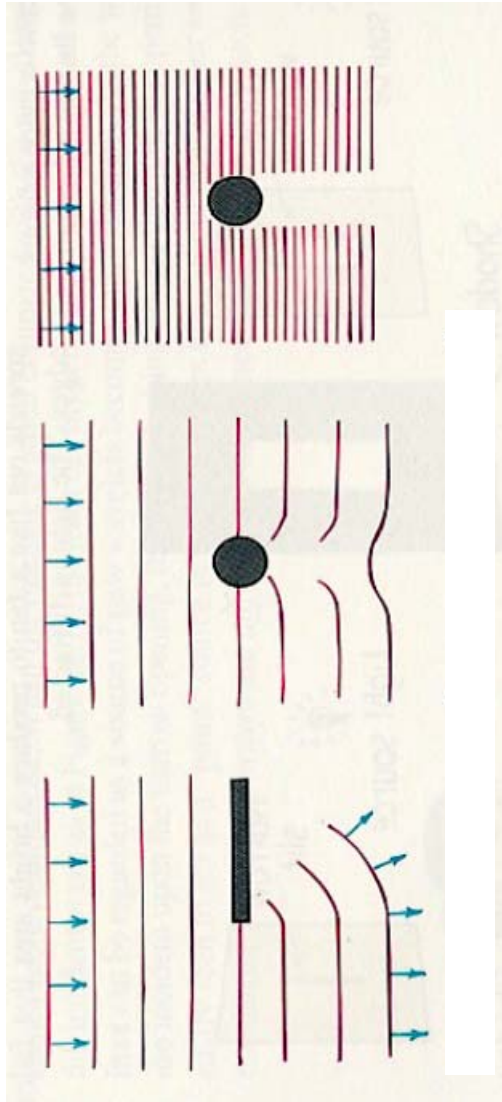
Con esta teoría Maxwell explicó:
La polarización
El transporte de energía y momentum
La velocidad de la luz
El espectro electromagnético



$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \lambda f$$

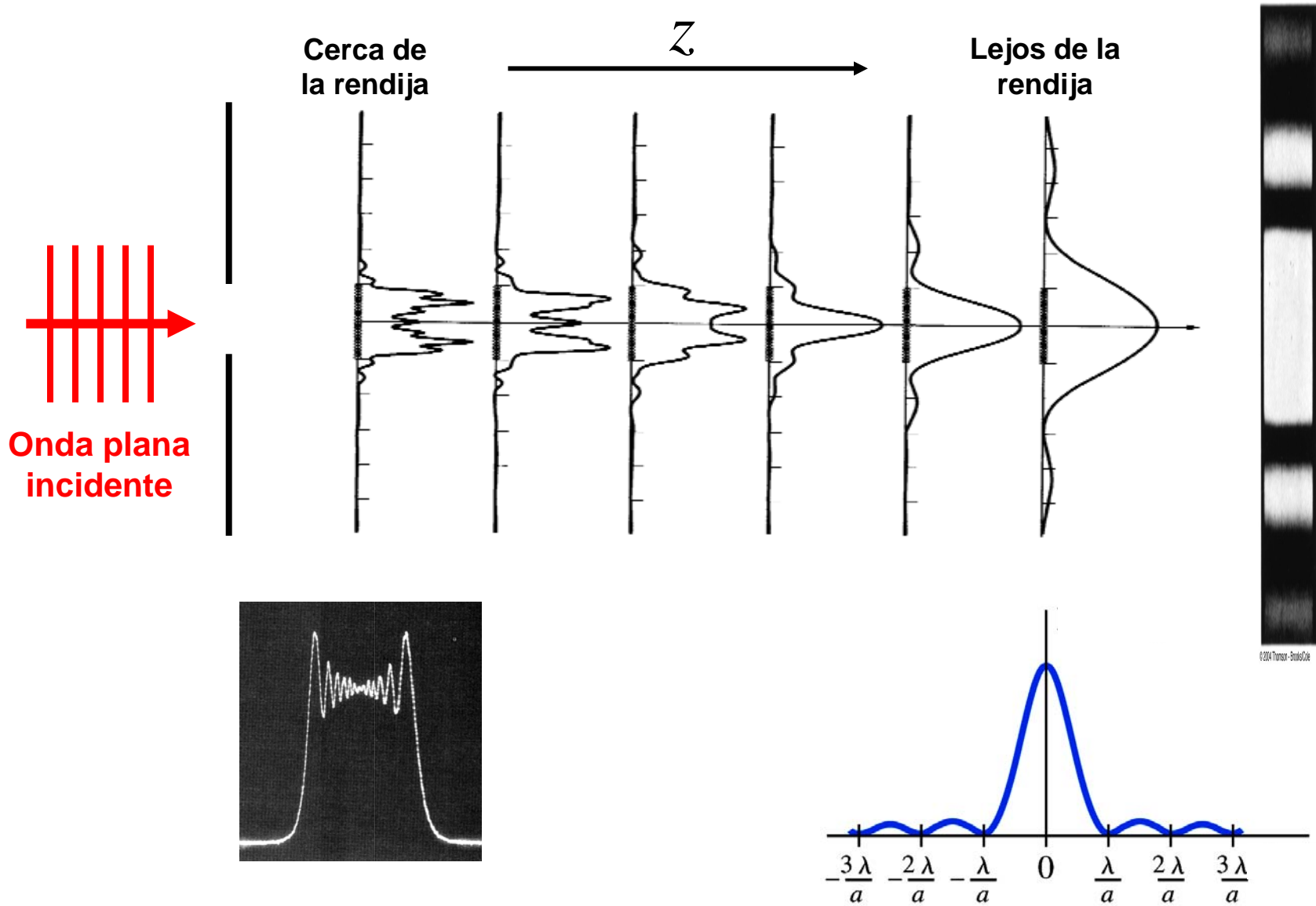


Concepto de difracción

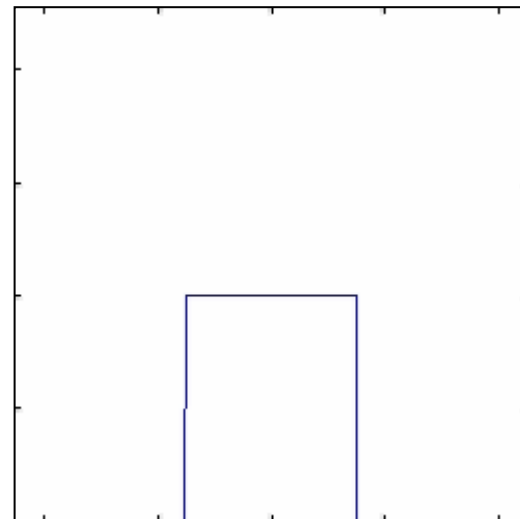
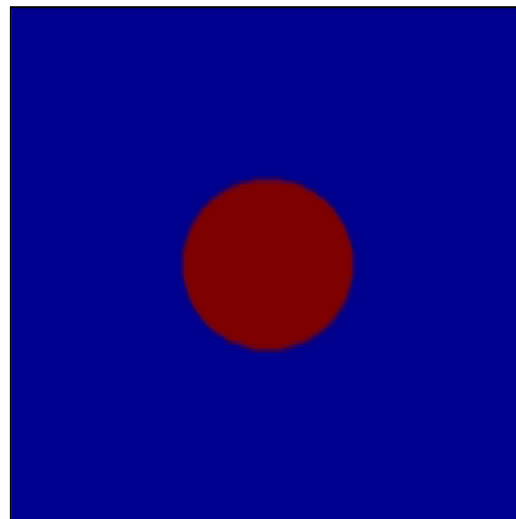
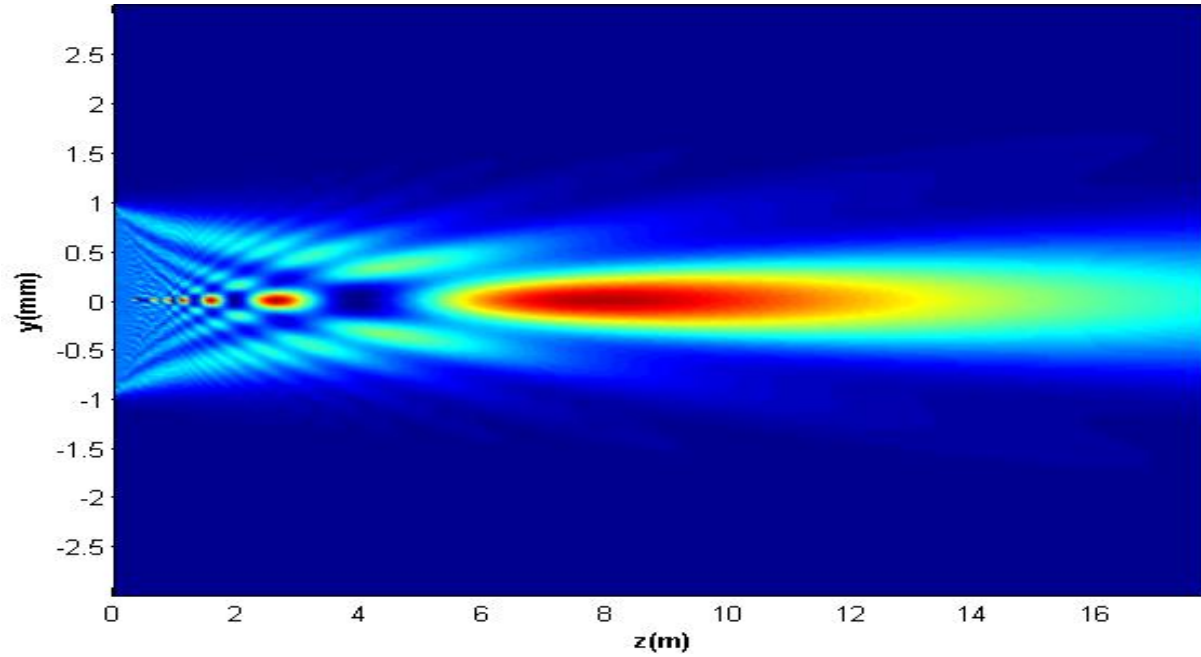
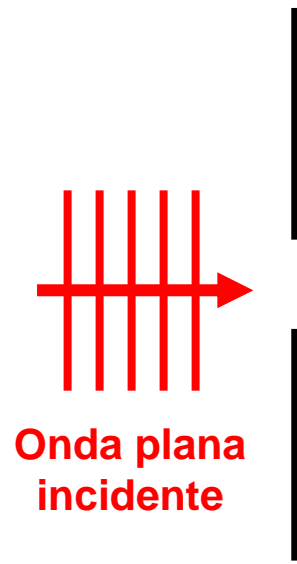


La difracción es mucho más notable cuando las dimensiones del obstáculo son similares a la longitud de onda de la onda.

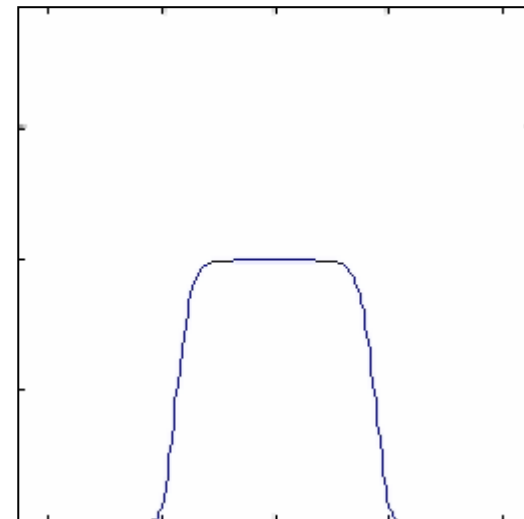
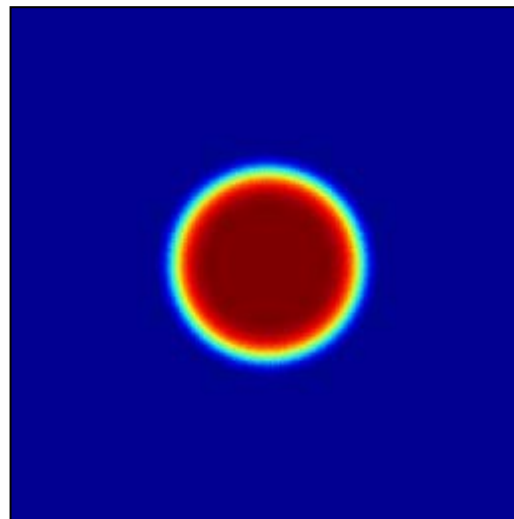
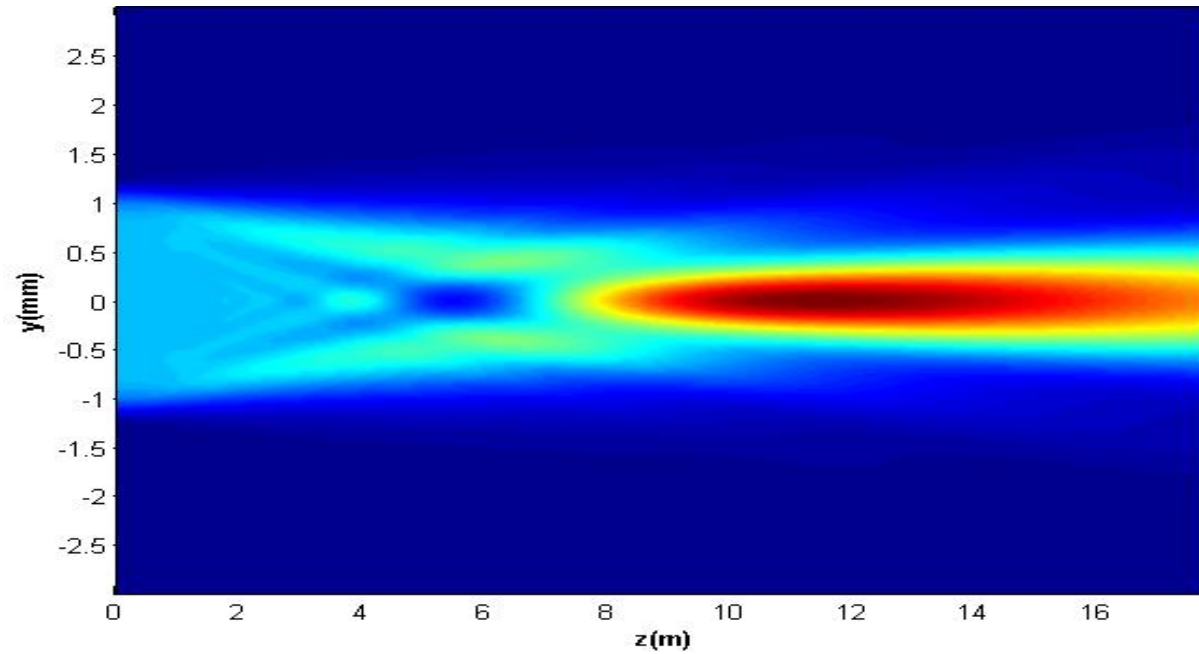
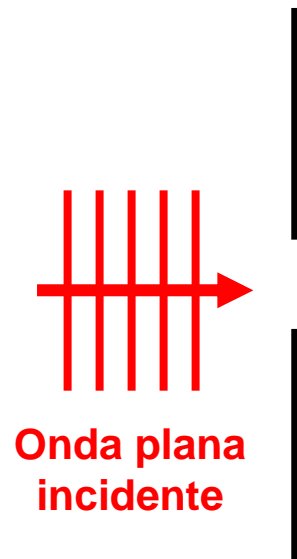
Difracción de una apertura circular



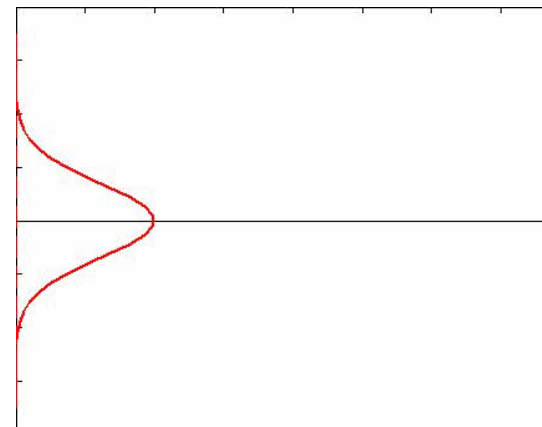
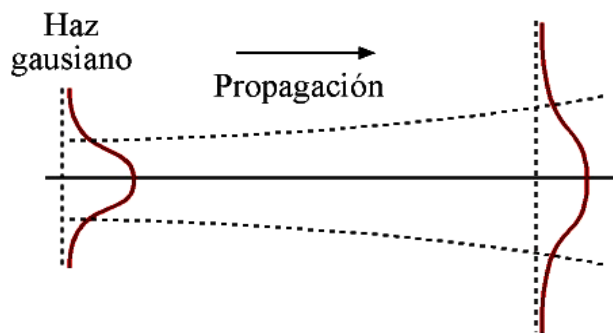
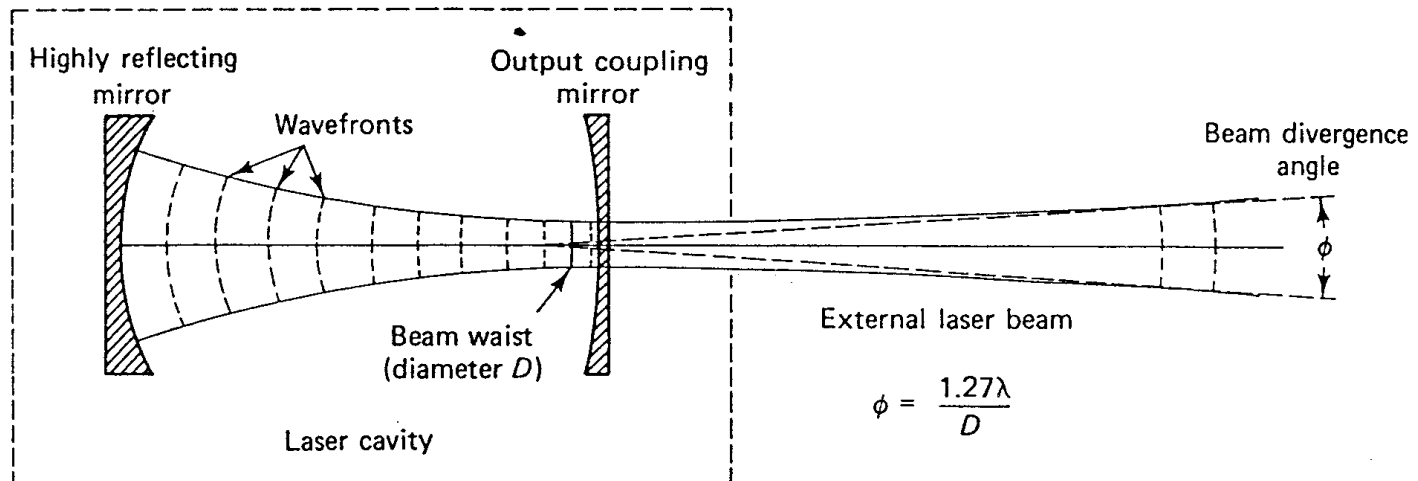
Difracción de una apertura circular



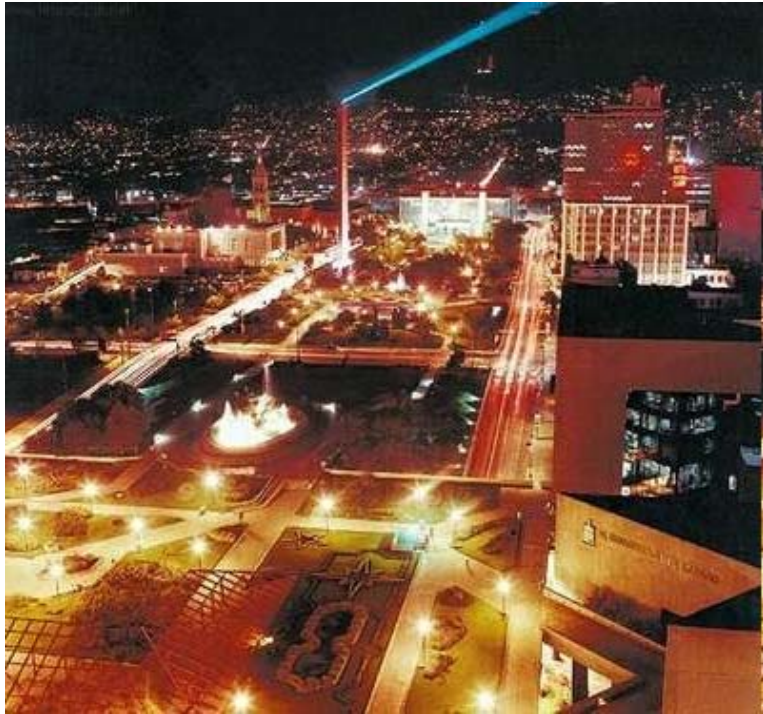
Difracción de una apertura circular apodizada



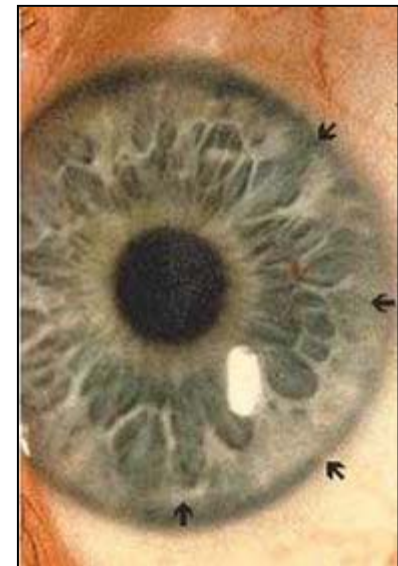
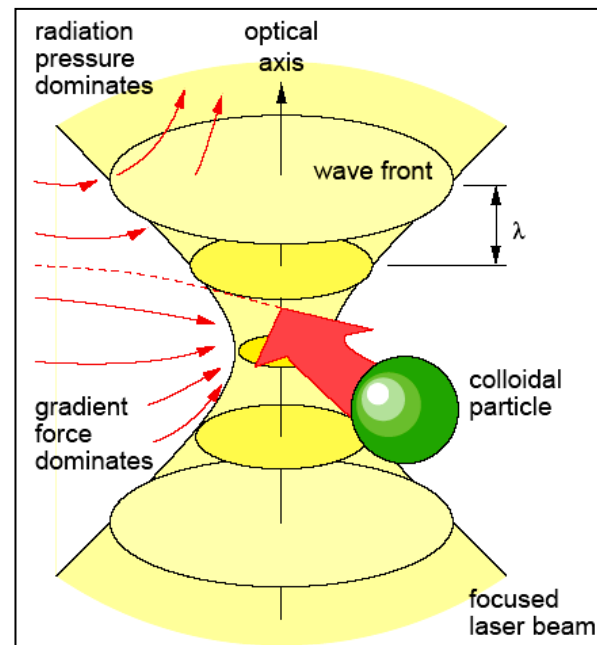
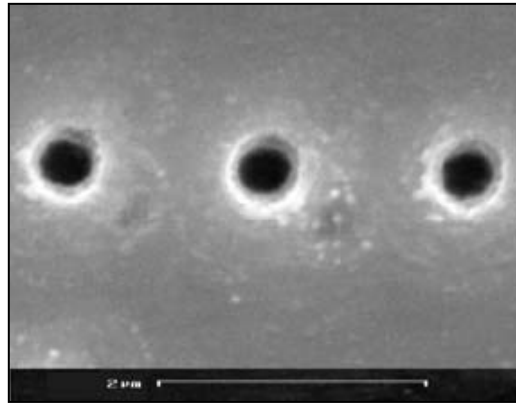
Los rayos laser también se difractan !!!



Los rayos laser también se difractan !!!



Difracción puede ser perjudicial o provechosa



¿Cómo podemos anular la difracción de un perfil de luz?

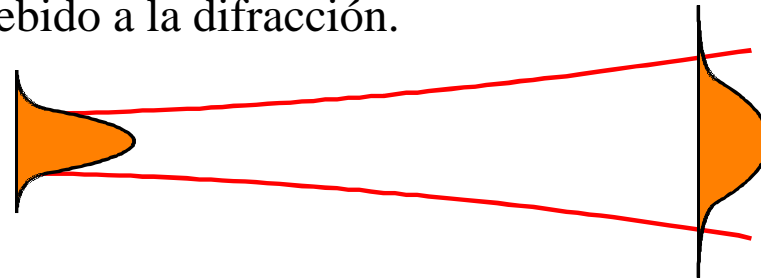
¿Se puede?

Si
usando materiales no lineales

Solitones Ópticos en medios no lineales

Ensanchamiento debido a la difracción.

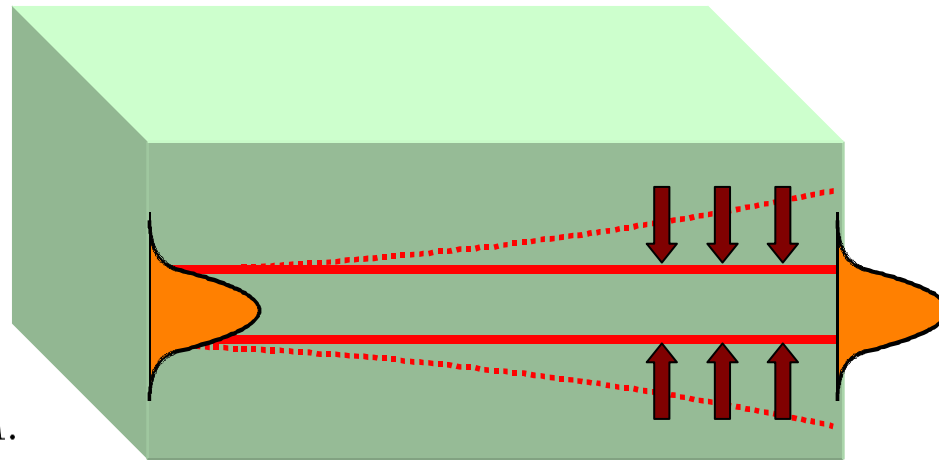
Medio lineal



$$P(t) = \epsilon_0 [\chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \dots]$$

Soliton espacial

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

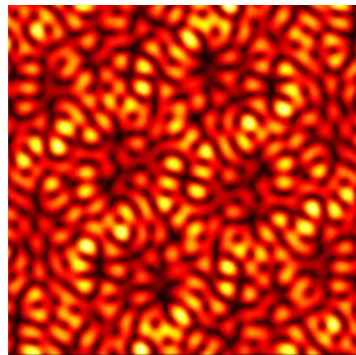


Compensación de la difracción debido al auto-enfocamiento no lineal

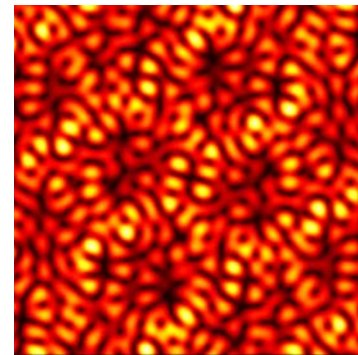
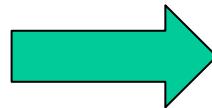
Pero,

¿Podemos construir perfiles que no se difracten mientras viajan en aire?

¿Se puede?

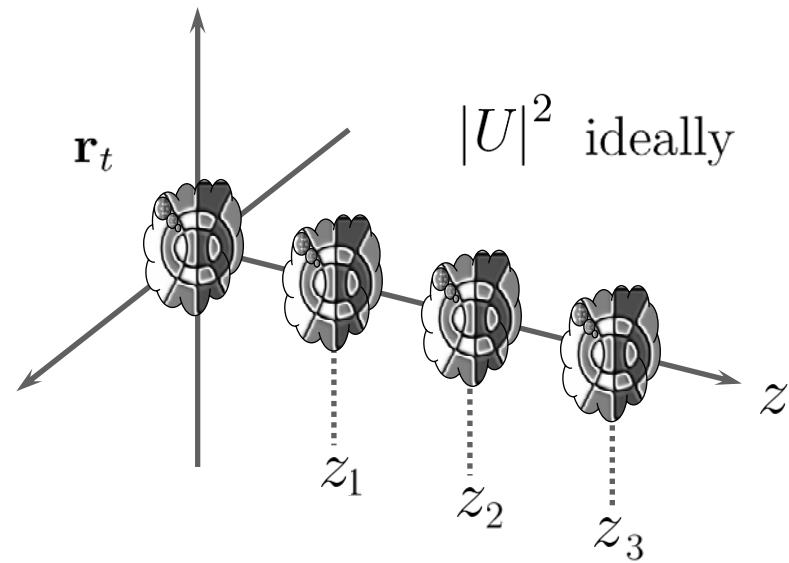


$z = 0$

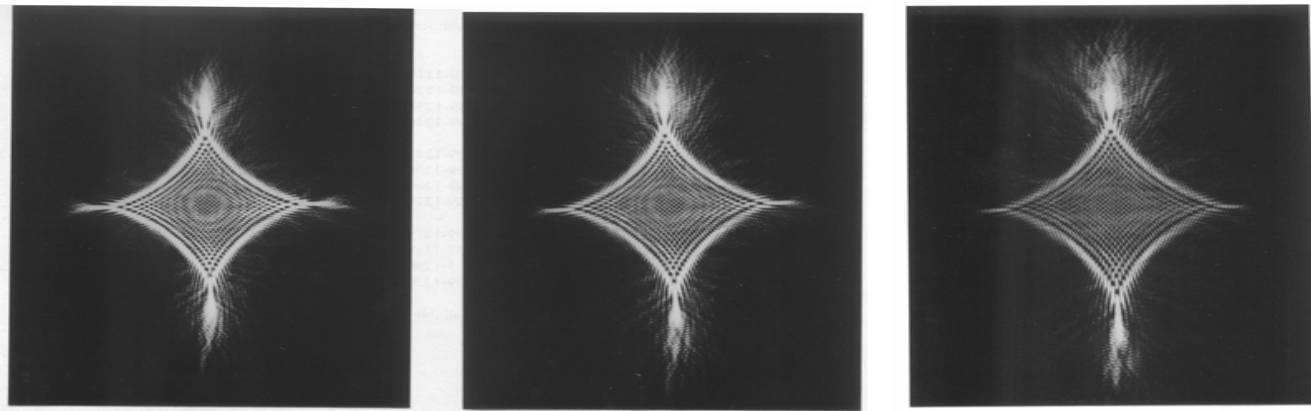


$z > 0$

Concepto de un haz adifraccional



1 cm



$z = 0$

$z = 2$ m

$z = 4$ m

Primeros artículos 1987: Bessel beams

PHYSICAL REVIEW LETTERS

VOLUME 58

13 APRIL 1987

NUMBER 15

Diffraction-Free Beams

J. Durnin and J. J. Miceli, Jr.

The Institute of Optics, University of Rochester, Rochester, New York 14627

and

J. H. Eberly^(a)

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 20 October 1986)

It was recently predicted that nondiffracting beams, with beam spots as small as a few wavelengths, can exist and propagate in free space. We report the first experimental investigation of these beams.

PACS numbers: 03.50.-z, 03.65.-w, 41.10.Hv, 42.10.Hc

Vol. 4, No. 4/April 1987/J. Opt. Soc. Am. A 651

Exact solutions for nondiffracting beams. I. The scalar theory

J. Durnin

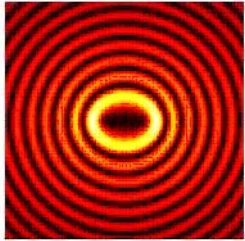
The Institute of Optics, University of Rochester, Rochester, New York 14627

Received June 12, 1986; accepted November 24, 1986

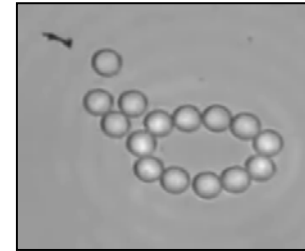
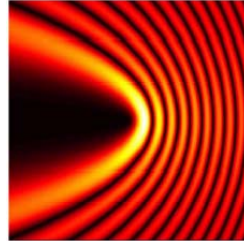
We present exact, nonsingular solutions of the scalar-wave equation for beams that are nondiffracting. This means that the intensity pattern in a transverse plane is unaltered by propagating in free space. These beams can have extremely narrow intensity profiles with effective widths as small as several wavelengths and yet possess an infinite depth of field. We further show (by using numerical simulations based on scalar diffraction theory) that physically realizable finite-aperture approximations to the exact solutions can also possess an extremely large depth of field.

Haces adifraccionales y sus familiares

Haces Mathieu



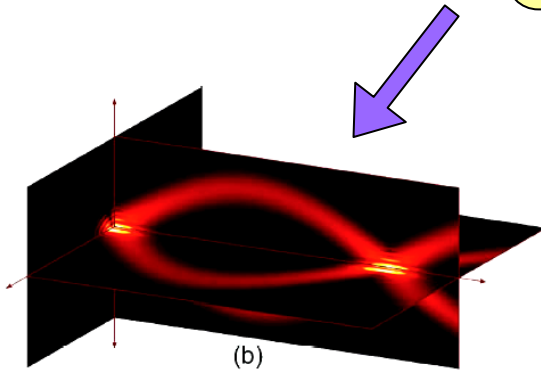
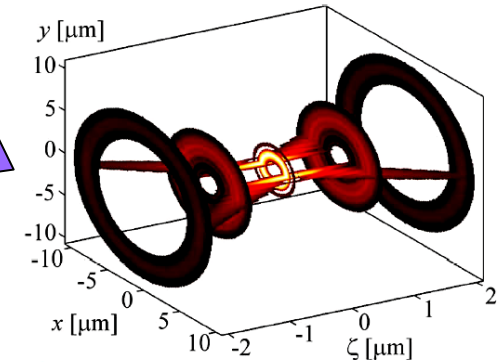
Haces Parabólicos



Aplicación en atrapamiento

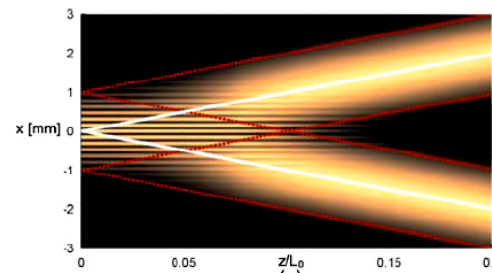
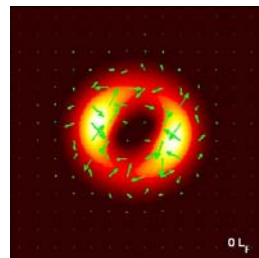
Haces adifraccionales y Helmholtz-Gauss

Mathieu y Parabolic X waves



HG en sistemas ABCD

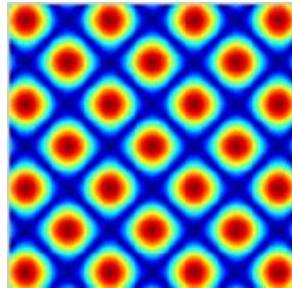
Modelo vectorial



HG en medios absorbentes

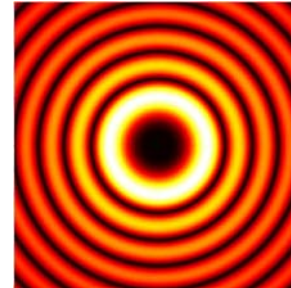
Cuatro grandes familias de haces adifraccionales

Ondas planas



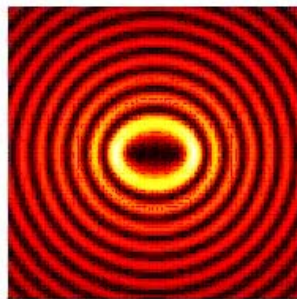
(~ Siglo 18)

Haces Bessel



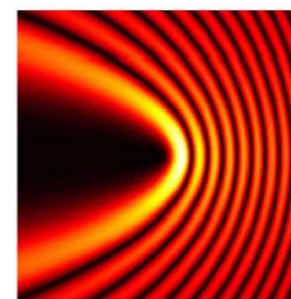
J. Durnin y J. H. Eberly (1987)

Haces Mathieu



J. C. Gutiérrez-Vega y S. Chavez-Cerda
(2000)

Haces Parabolicos



M. A. Bandrés y J. C. Gutiérrez-Vega
(2004)

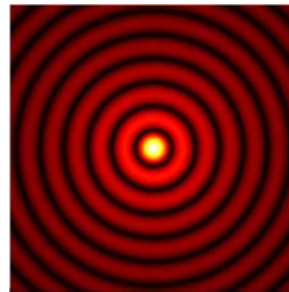
Haces Bessel

Distribución de campo:

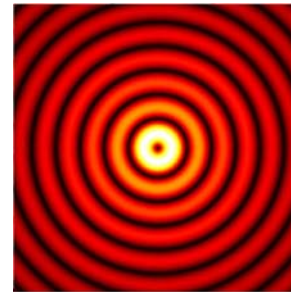
$$U(\mathbf{r}) = J_m(k_t r) \exp(im\theta) \exp(ik_z z)$$
$$= \exp(ik_z z) \int_{-\pi}^{\pi} \underbrace{\left[\frac{(-i)^m}{2\pi} \exp(im\varphi) \right]}_{\text{Espectro angular}} \exp[ik_t r \cos(\varphi - \theta)] d\varphi$$

Espectro angular: $A(\varphi) \propto \exp(im\varphi)$

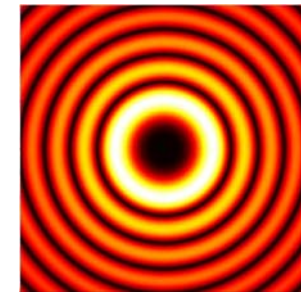
Distribución de intensidad



$m = 0$

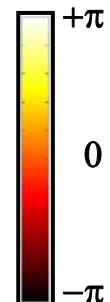
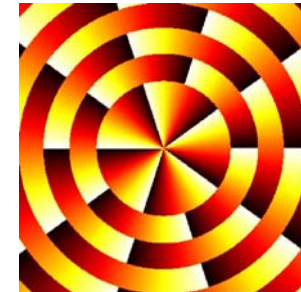


$m = 1$



$m = 5$

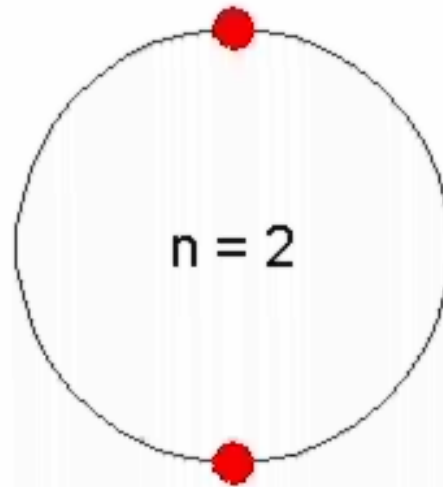
Distribución de fase



Adding plane waves to build up Bessel beams

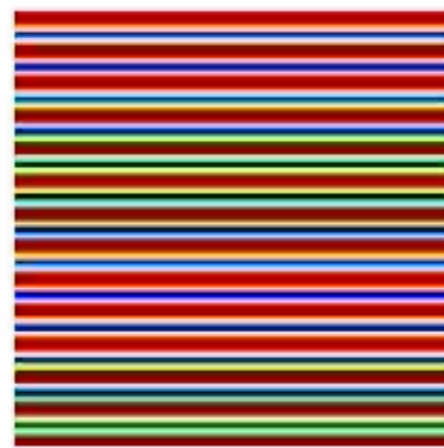
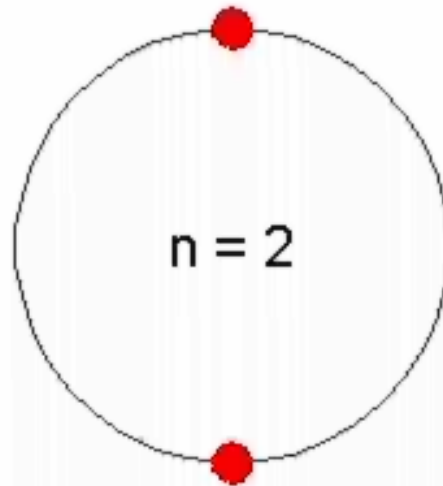
Bessel beam J_0

$$A(\phi) = 1$$

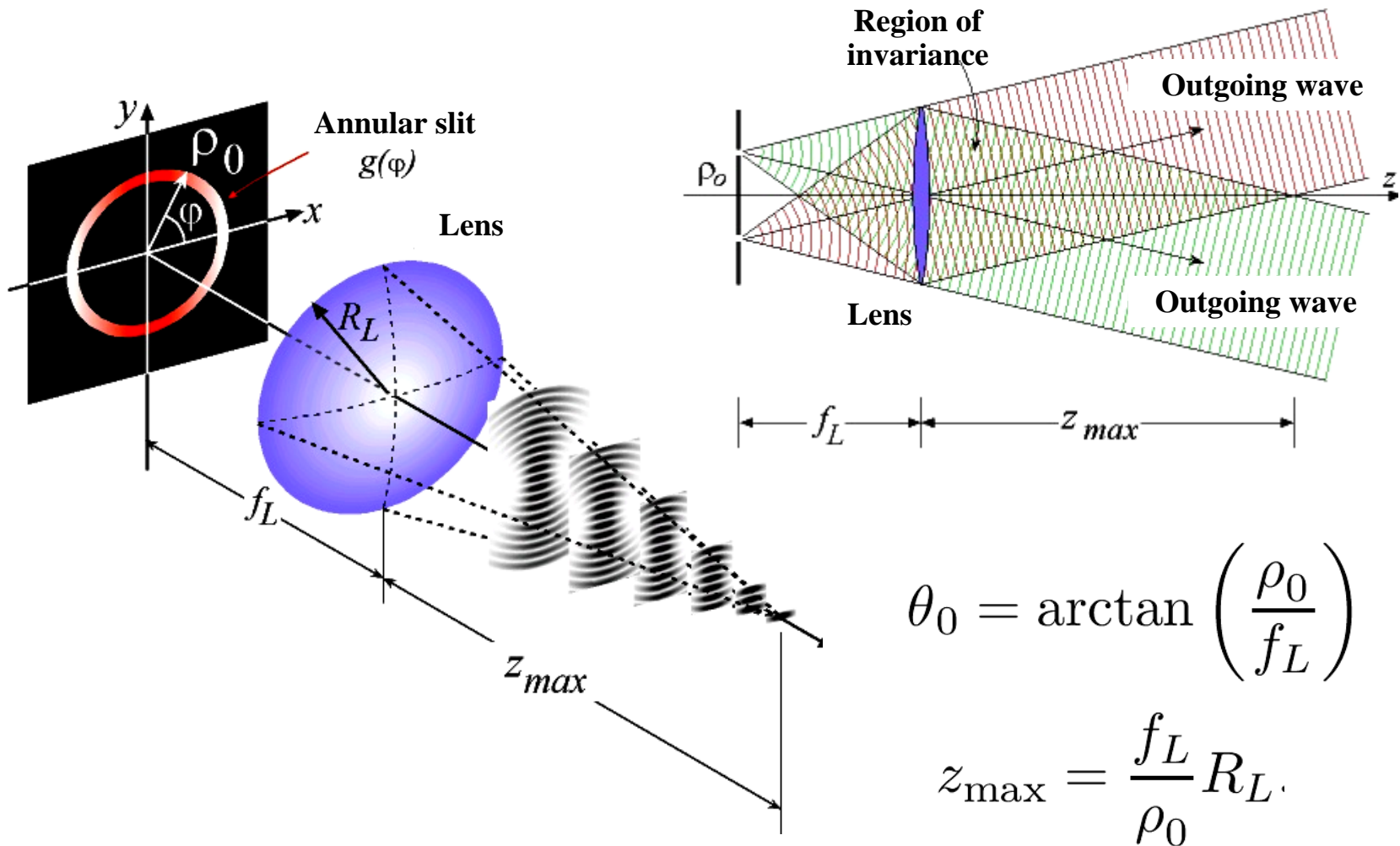


Bessel beam J_2

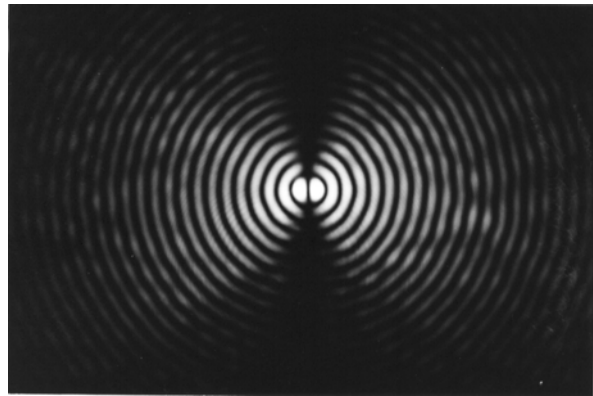
$$A(\phi) = \exp(im\phi)$$



Arreglo simple para producir haces no difractivos

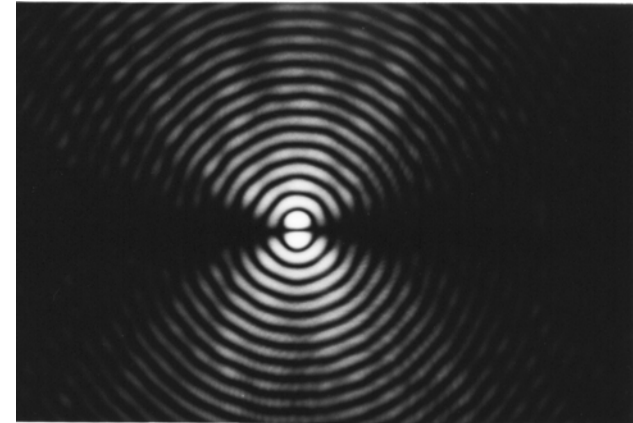


Some results



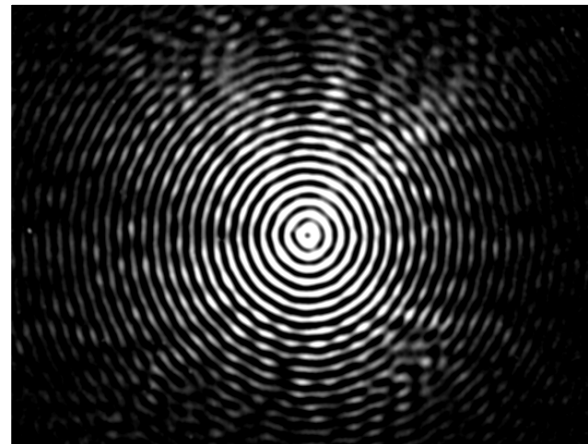
$$J_1(k_t r)\cos(\varphi)$$

+ *i*



$$J_1(k_t r)\sin(\varphi)$$

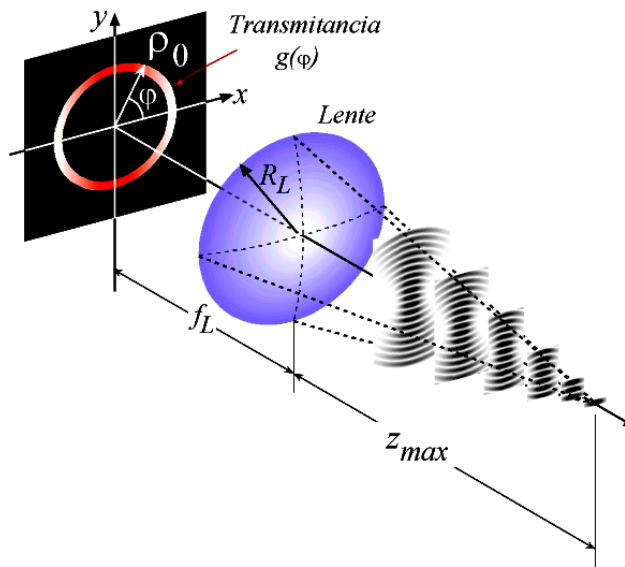
$$J_1(k_t r)\exp(i\varphi)$$



↑
0.8 mm
↓

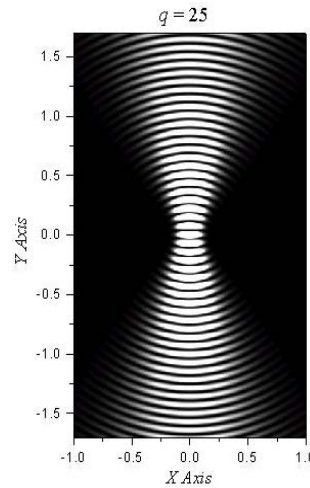
Primera observación experimental de un haz Mathieu

Arreglo tipo Durnin

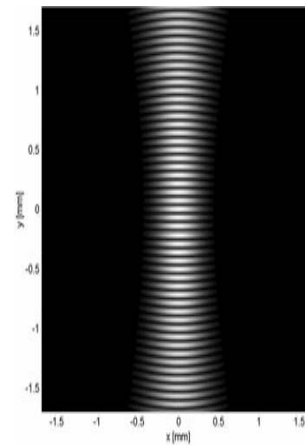


J. C. Gutiérrez-Vega *et al.*,
Opt. Comm., **195**, 35-40, 2001

Teoría

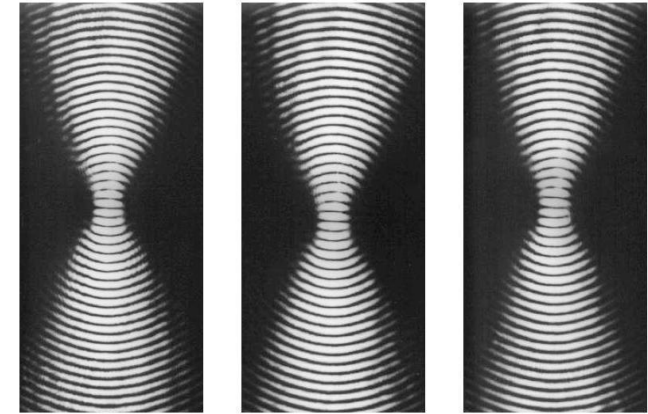


$q = 25$



$q = 525$

Experimento



a)

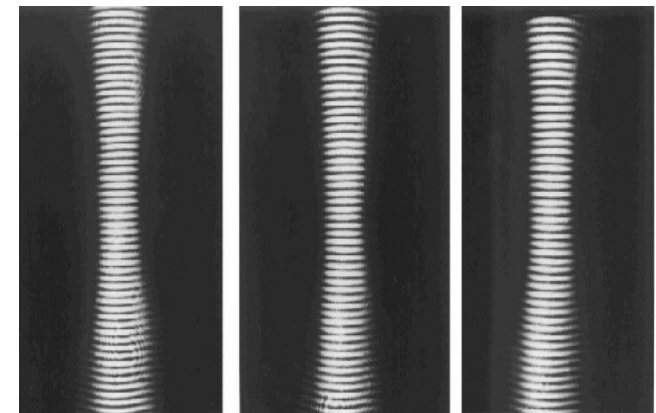
b)

c)

a) 0 m

b) 5 m

c) 10 m

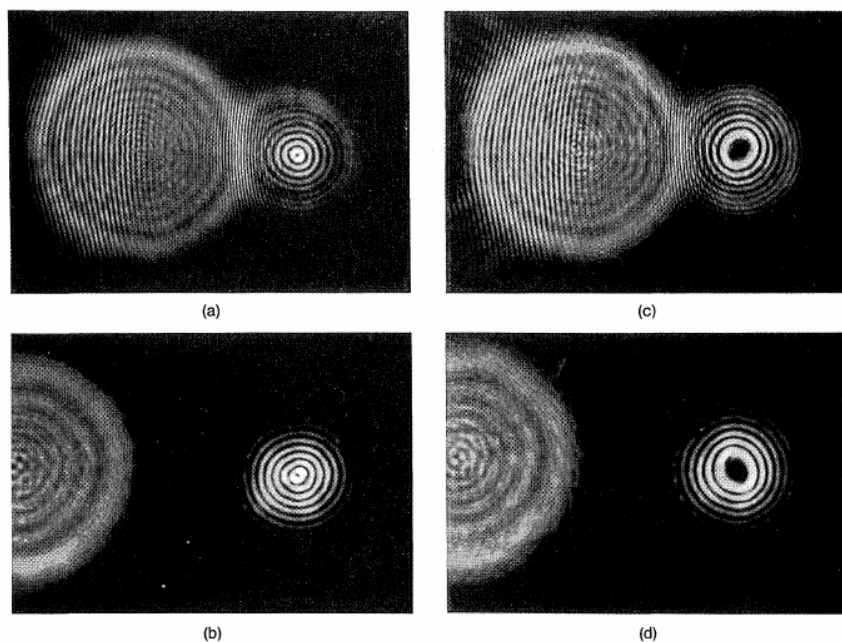


a)

b)

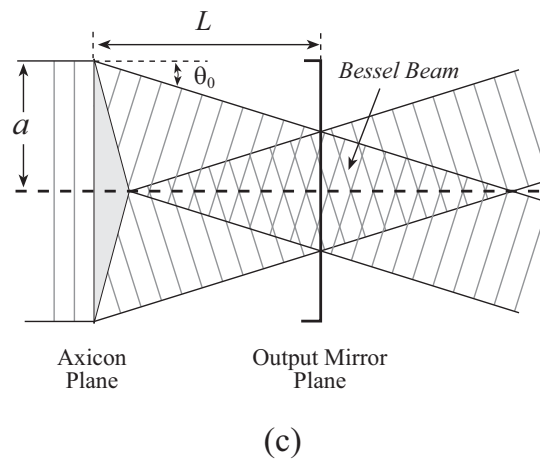
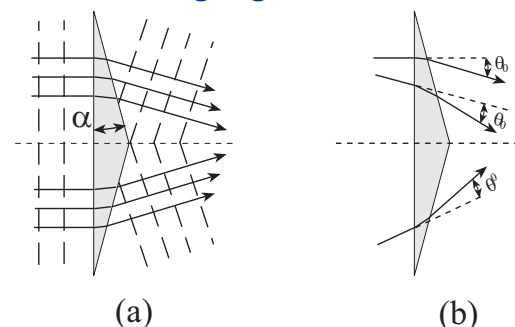
c)

Haces no difractivos se pueden construir con hologramas



A. Vasara, J. Turunen, and A. Friberg, "Realization of general nondiffracting beams with computer-generated holograms," J. Opt. Soc. Am. A 6, 1748- (1989)

An axicon transforms a plane wave into a converging conical wave

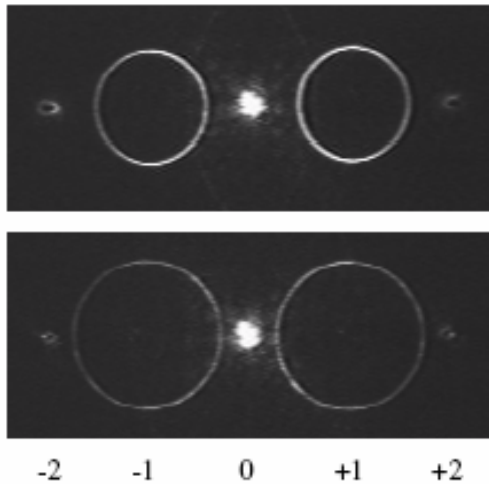
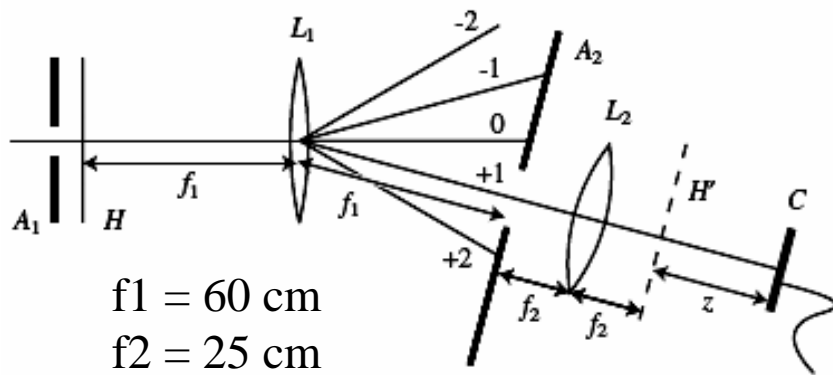


Converging conical waves build up the BB

Z. Jaroszewicz, A. Burvall, and A. T. Friberg, "Axicon - the Most Important Optical Element" Opt. Phot. News, 16, 34-39 (2005)

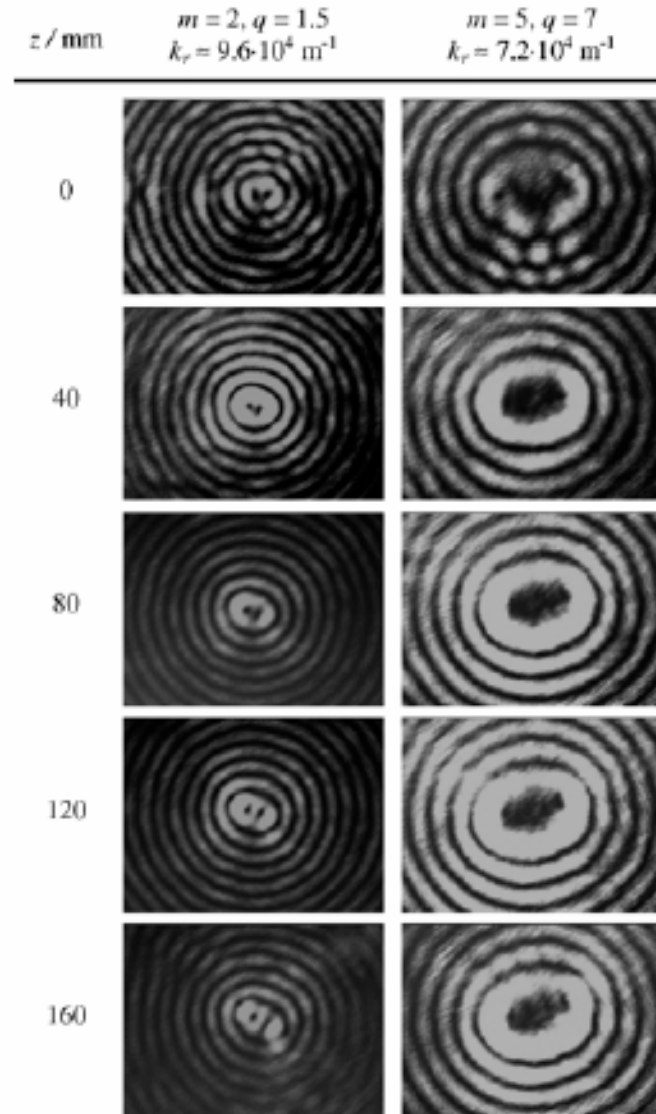
Generación holográfica de haces Mathieu helicoidales

Arreglo holográfico



Intensity at focal plane of L1

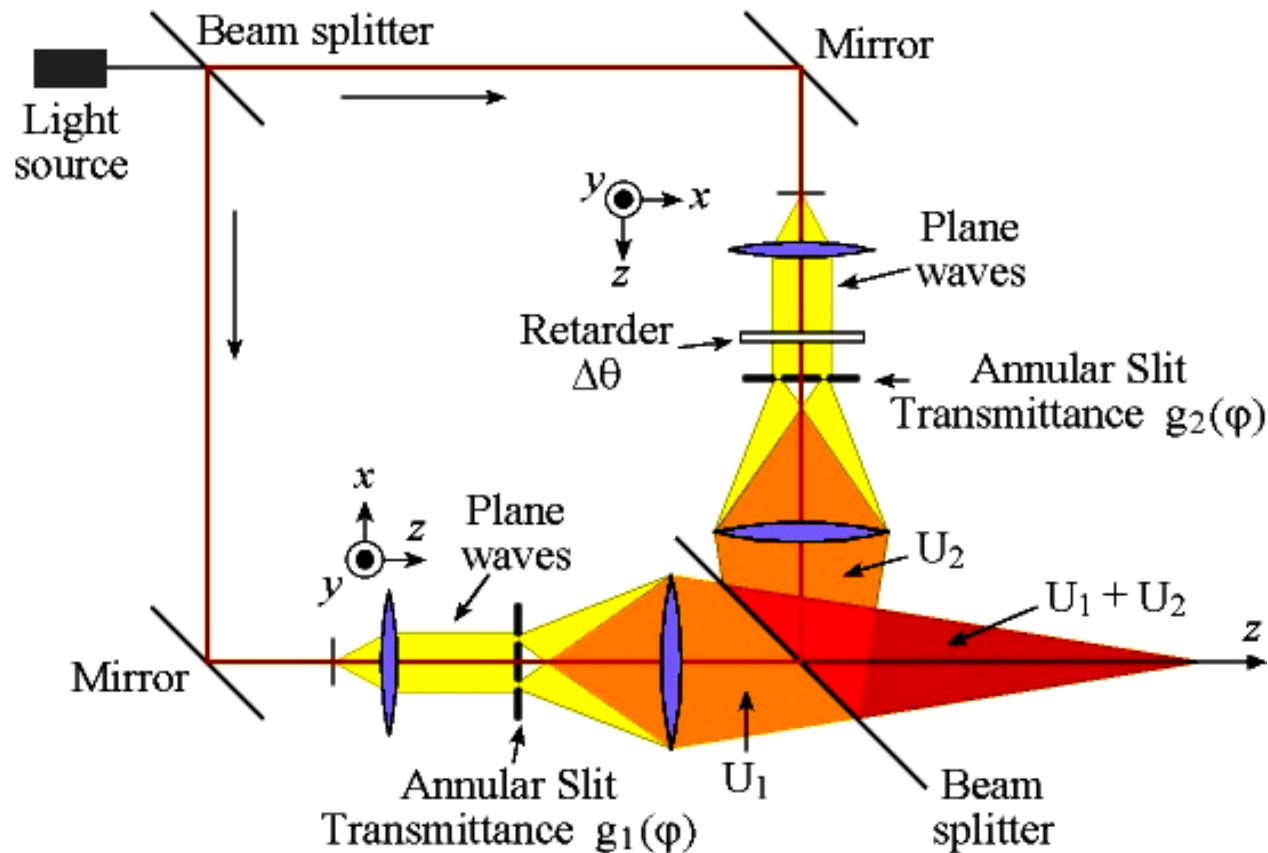
Diffraction order are identified at bottom



Interferómetro de Mach-Zehnder

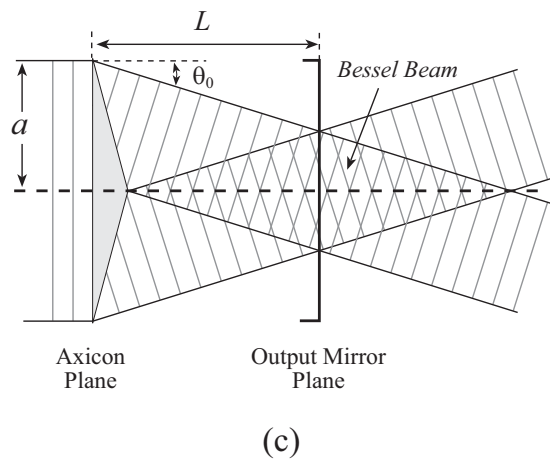
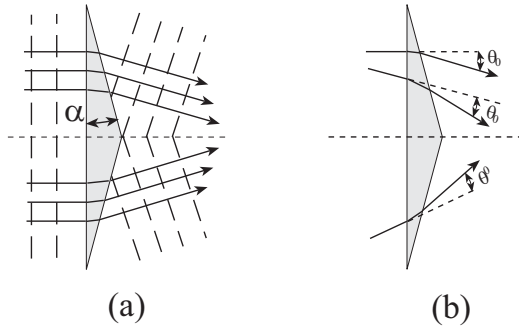
$$J_m(k_t r) \exp(im\varphi) = J_m(k_t r) \cos(m\varphi) + iJ_m(k_t r) \sin(m\varphi)$$

$$g_1(\varphi) = \cos(m\varphi), \quad g_2(\varphi) = \sin(m\varphi)$$



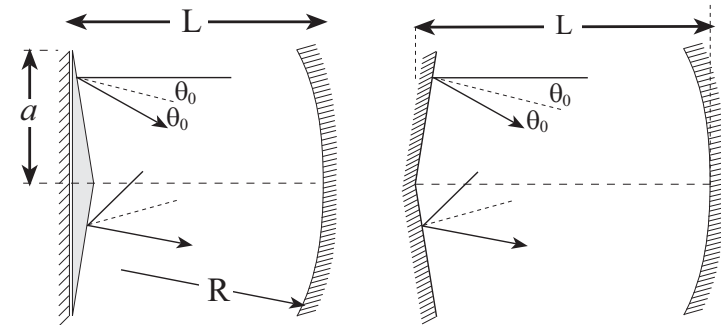
Métodos activos para general haces adifraccionales

An axicon transforms a plane wave into a converging conical wave

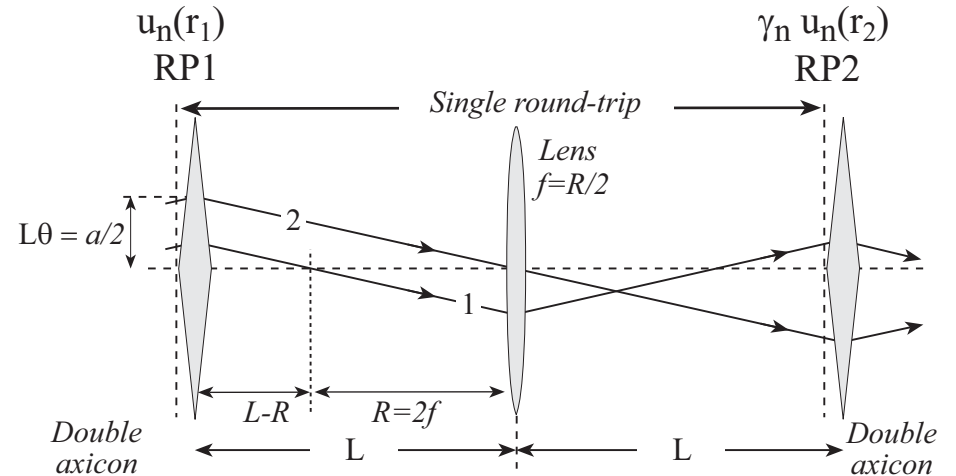


Converging conical waves build up the Bessel beam

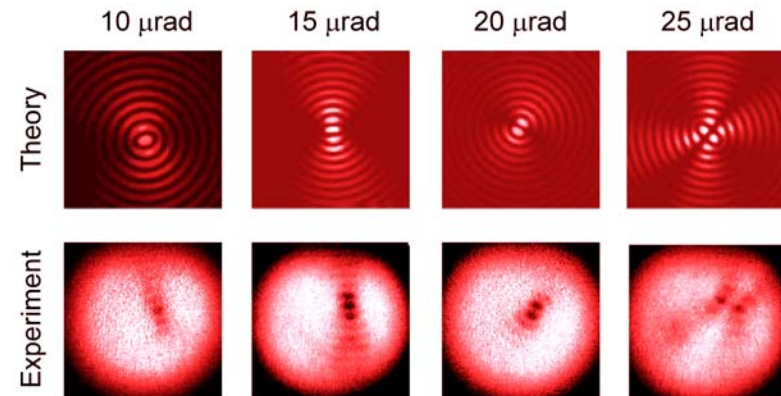
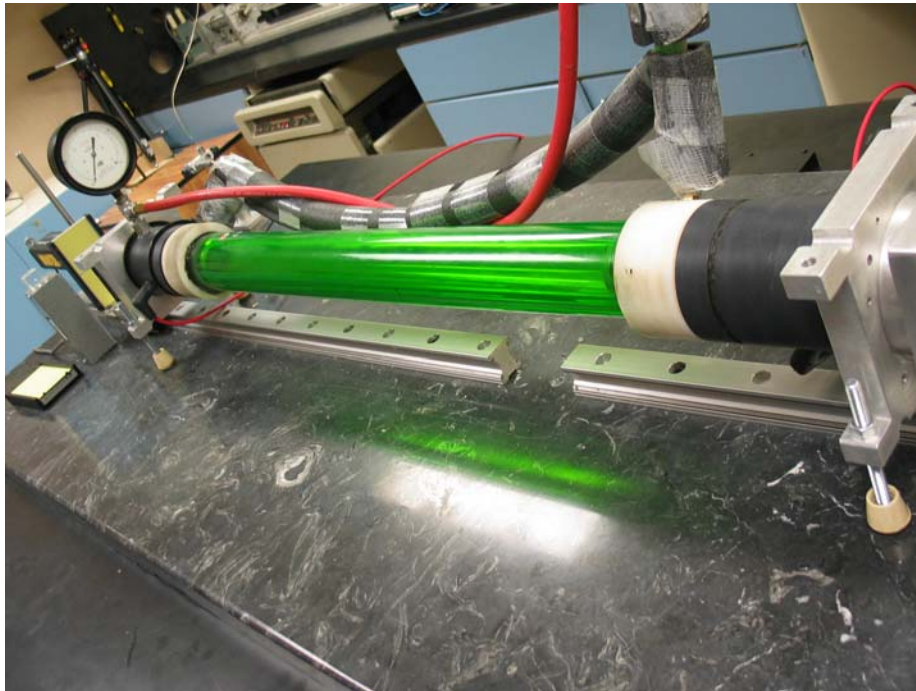
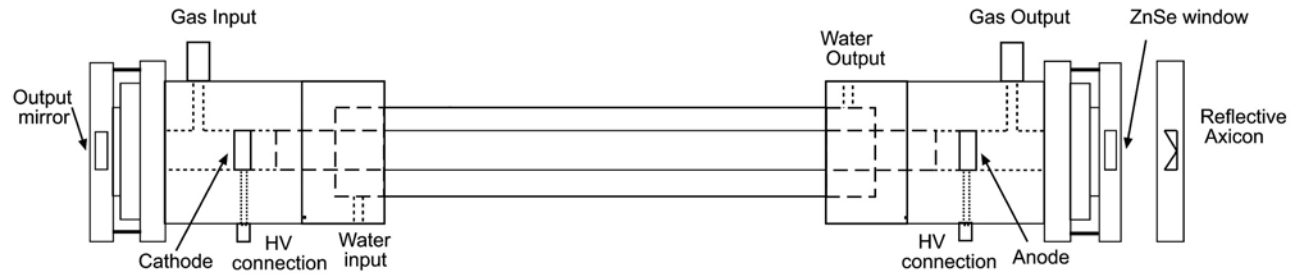
Resonator with refractive and reflective axicon



$$L = \frac{a}{2 \tan \theta_0} \approx \frac{a}{2 \theta_0} = \frac{a}{2(n-1)\alpha}$$

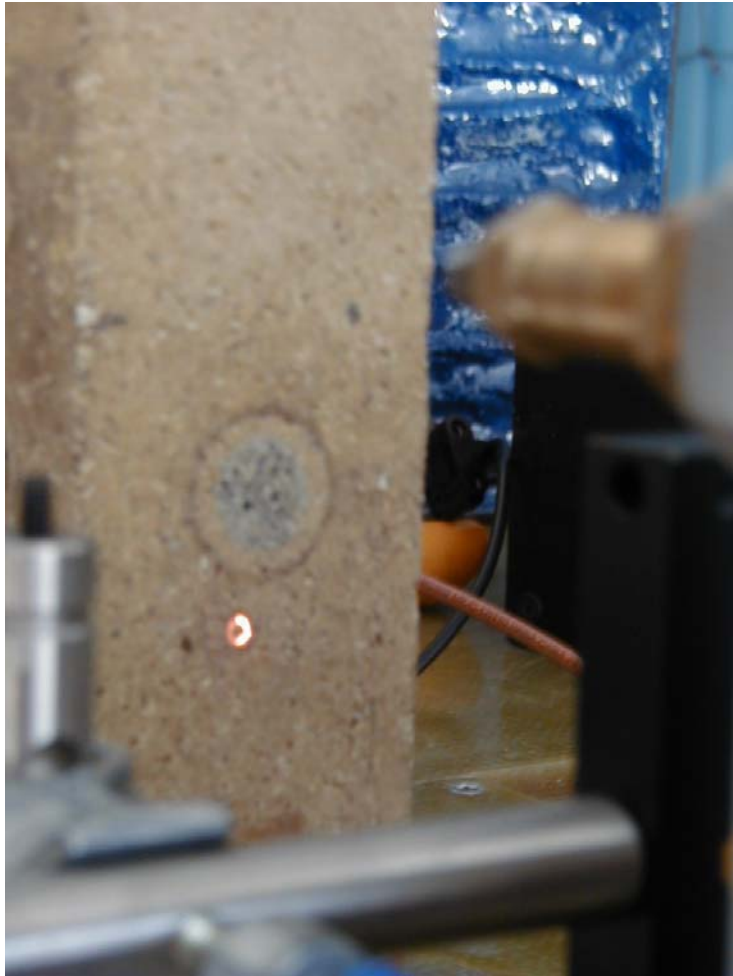


Resonador Bessel-Gauss de CO₂

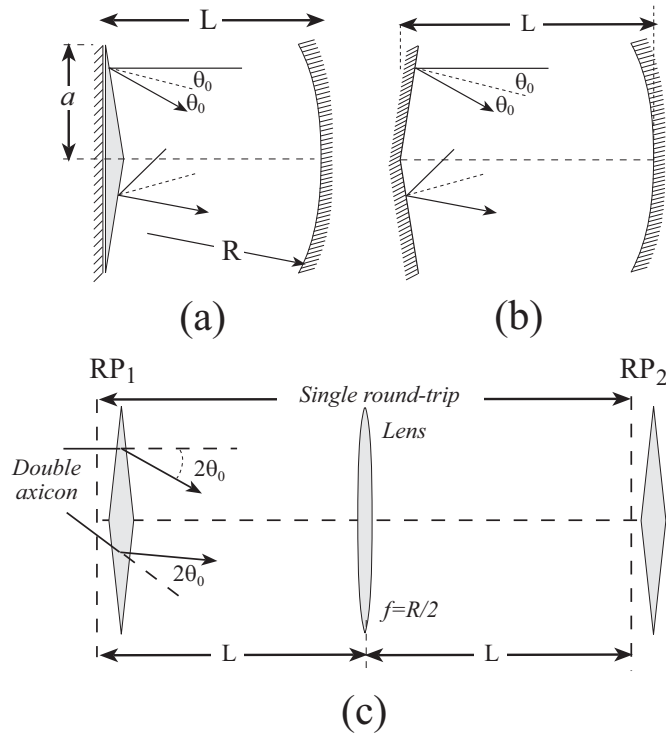


M. Alvarez, et al, "Construction and characterization of CO₂ laser with an axicon based Bessel-Gauss resonator," SPIE Vol. 5708-19, 323-331 (2005)

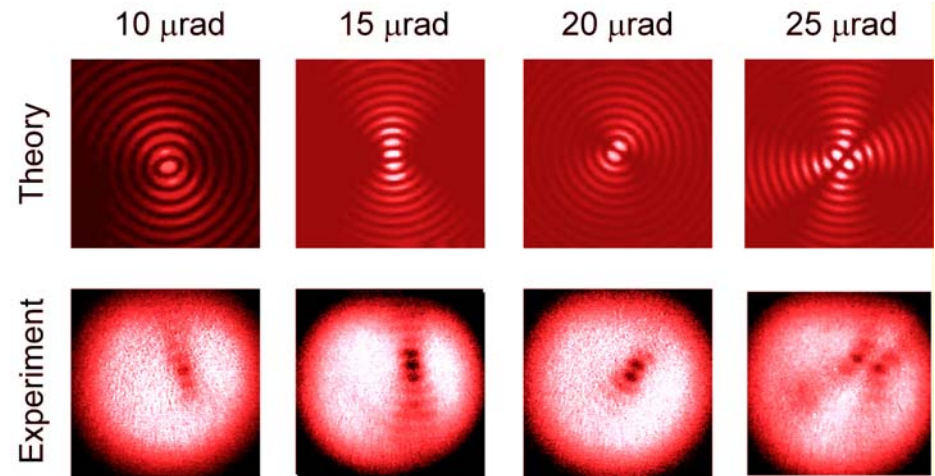
Enfocamiento de un haz Bessel



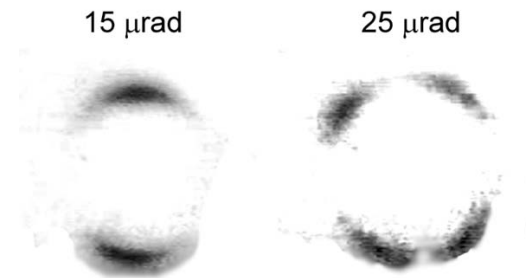
Haces Mathieu en un resonador laser



Disaligned cavity

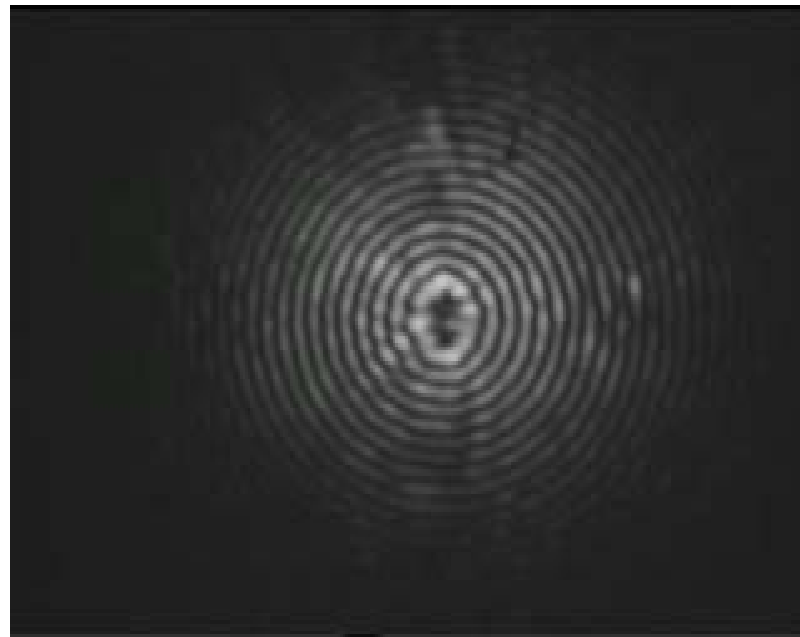
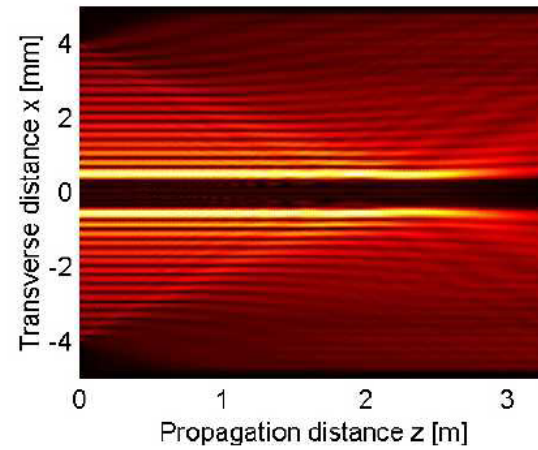
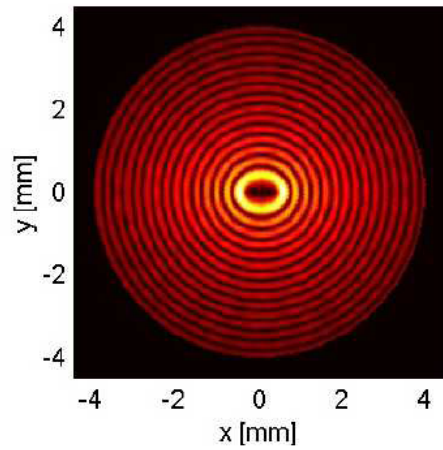


and at the focal plane



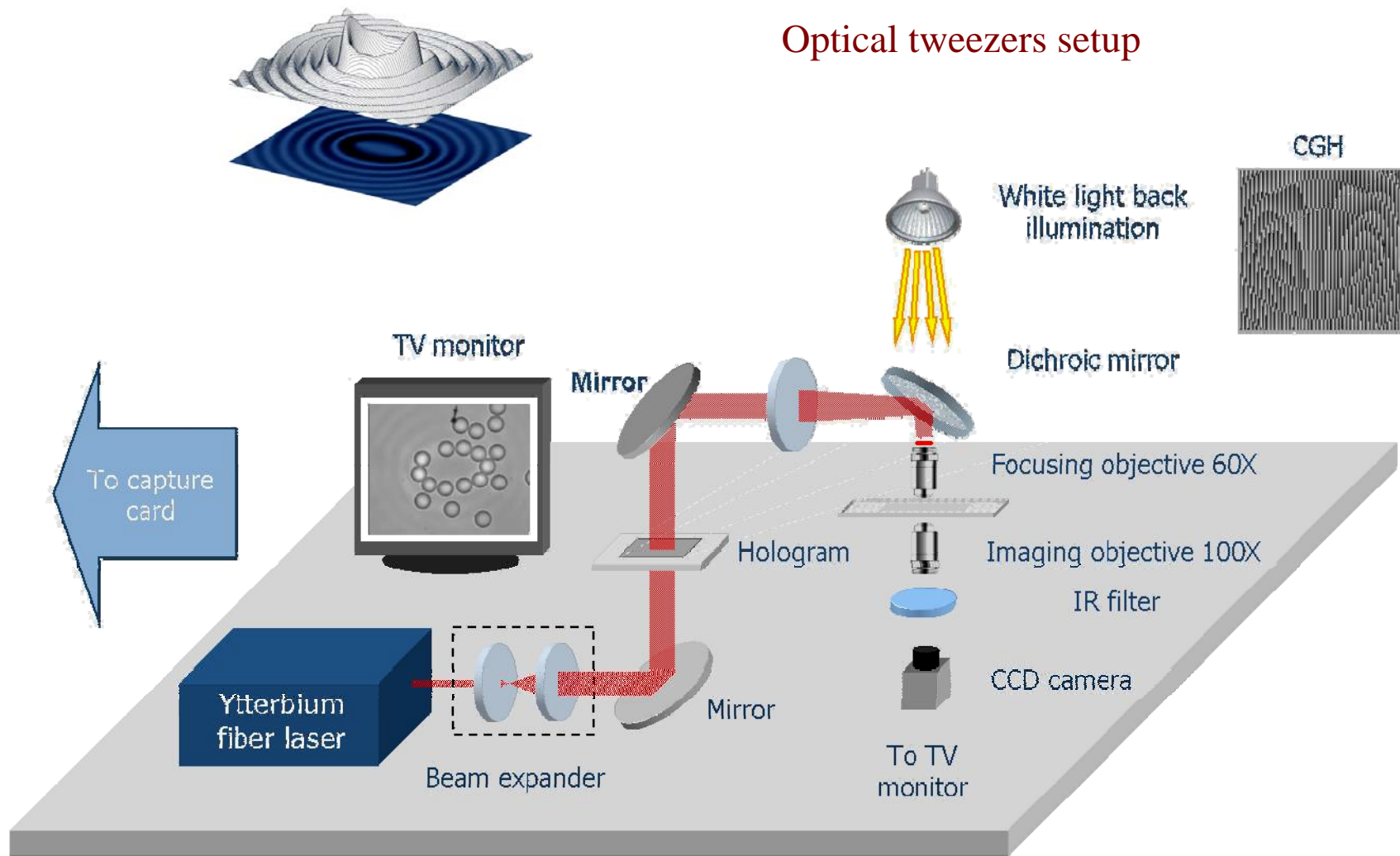
M. Alvarez, et al, "Construction and characterization of CO₂ laser with an axicon based Bessel-Gauss resonator," SPIE Vol. 5708-19, 323-331 (2005)

Propagación helicoidal de un haz óptico Mathieu



1 cm

Orbital Angular Momentum transfer using Mathieu beams



Orbital Angular Momentum transfer using Mathieu beams



**Orbital angular momentum transfer
in helical Mathieu beams [1]**

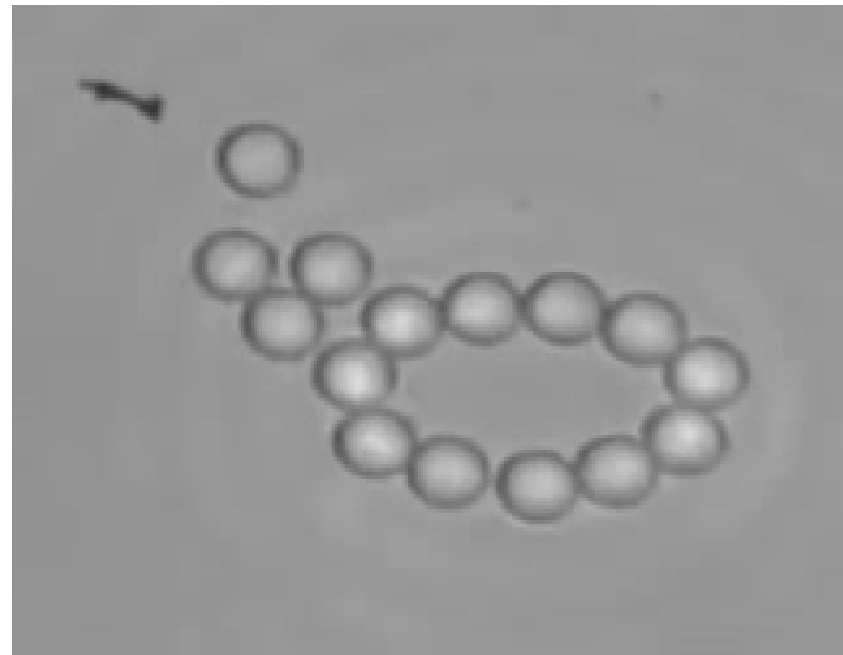
Polystyrene particles

Particle diameter: $3 \mu\text{m}$

Beam power: 1.3 W

$m=7$

$q=15$



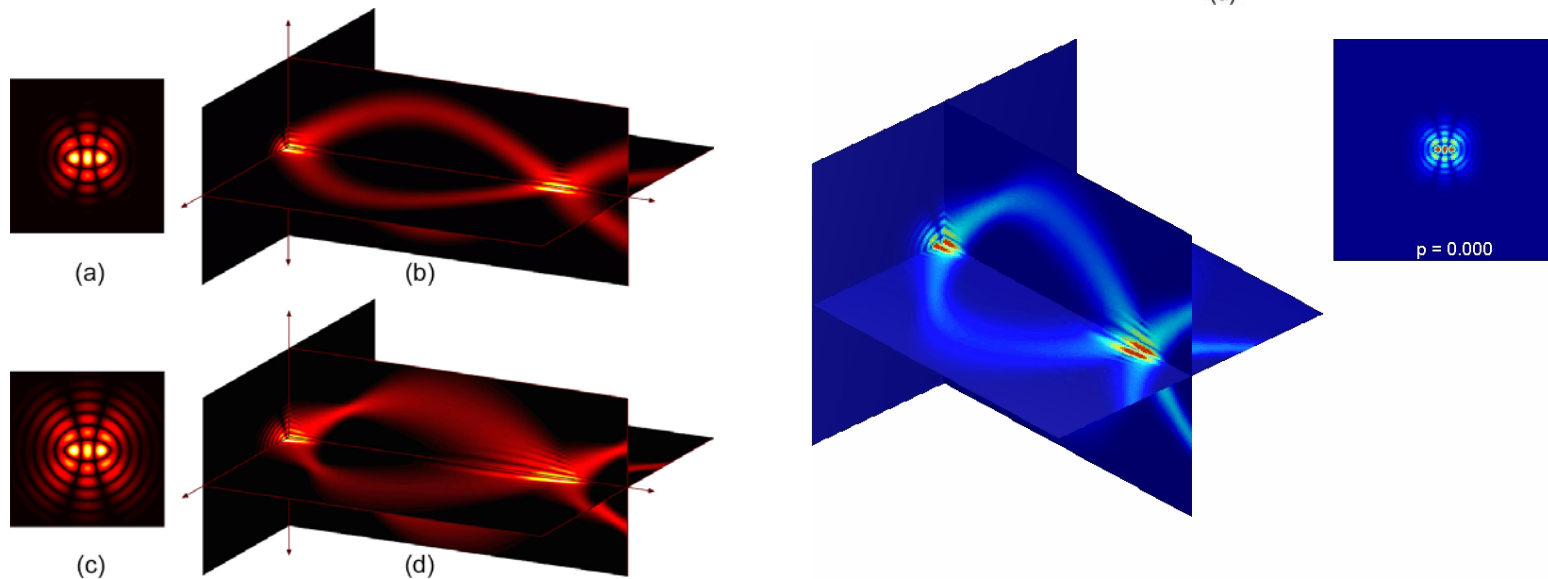
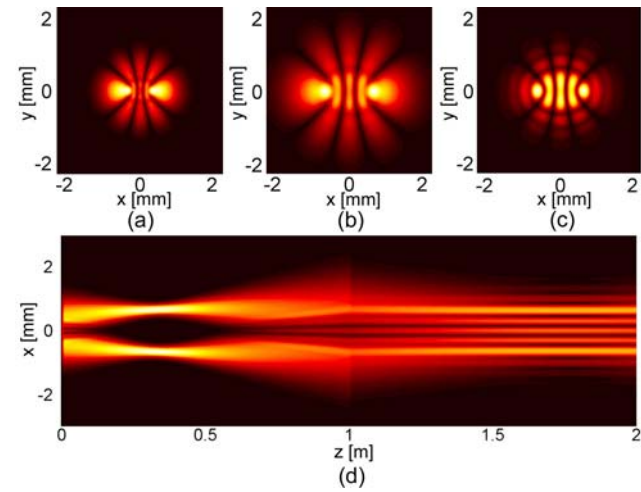
[1] C. López-Mariscal, J. C. Gutiérrez-Vega, G. Milne and K. Dholakia, Opt. Express, **14**, 4182 (2006)

Propagando haces en medios lineales ABCD

$$U_2(\mathbf{r}_2) = \exp\left(\frac{\kappa_1 \kappa_2 B}{i2k}\right) \text{GB}(\mathbf{r}_2, q_2) W(\mathbf{r}_2; \kappa_2),$$

$$\text{GB}(\mathbf{r}_2, q_2) = \frac{\exp(ik\zeta)}{A + B/q_1} \exp\left(\frac{ikr_2^2}{2q_2}\right)$$

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}, \quad \kappa_2 = \frac{\kappa_1}{A + B/q_1}.$$



Vector Helmholtz-Gauss beams

First class vector beam solution

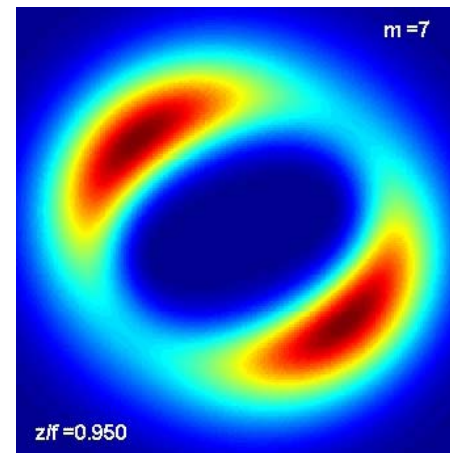
$$\begin{aligned} \mathbf{E}_t^{(1)} &= Z(\zeta) G(\mathbf{r}) \nabla_T W, \\ E_z^{(1)} &= -\frac{iZ(\zeta) G(\mathbf{r})}{\zeta} \left(\frac{k_t^2}{k} W + \frac{2}{kw_0} \nabla_T W \cdot \frac{\mathbf{r}_t}{w_0} \right), \\ \mathbf{H}_t^{(1)} &= \sqrt{\frac{\epsilon_0}{\mu_0}} Z(\zeta) G(\mathbf{r}) (\hat{\mathbf{z}} \times \nabla_T W), \\ H_z^{(1)} &= -\sqrt{\frac{\epsilon_0}{\mu_0}} \frac{2i}{kw_0} \frac{Z(\zeta) G(\mathbf{r})}{\zeta} (\hat{\mathbf{z}} \times \nabla_T W) \cdot \frac{\mathbf{r}_t}{w_0}, \end{aligned}$$

Second class vector beam solution

$$\begin{aligned} \mathbf{E}_t^{(2)} &= -Z(\zeta) G(\mathbf{r}) (\hat{\mathbf{z}} \times \nabla_T W), \\ E_z^{(2)} &= \frac{2i}{kw_0} \frac{Z(\zeta) G(\mathbf{r})}{\zeta} (\hat{\mathbf{z}} \times \nabla_T W) \cdot \frac{\mathbf{r}_t}{w_0}, \\ \mathbf{H}_t^{(2)} &= \sqrt{\frac{\epsilon_0}{\mu_0}} Z(\zeta) G(\mathbf{r}) \nabla_T W, \\ H_z^{(2)} &= -\sqrt{\frac{\epsilon_0}{\mu_0}} \frac{iZ(\zeta) G(\mathbf{r})}{\zeta} \left(\frac{k_t^2}{k} W + \frac{2}{kw_0} \nabla_T W \cdot \frac{\mathbf{r}_t}{w_0} \right) \end{aligned}$$

where $W(X,Y)$ is a solution of the 2D scalar Helmholtz equation

$$\nabla_T^2 W + k_t^2 W = 0.$$



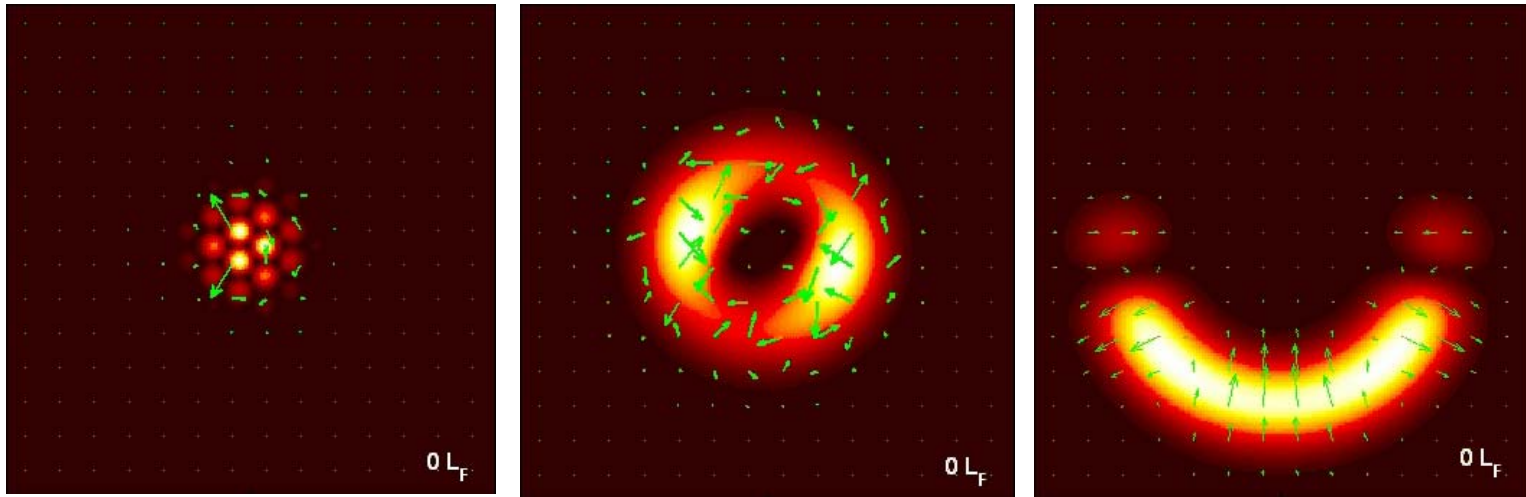
M. A. Bandres and J. C. Gutiérrez-Vega, "Vector Helmholtz-Gauss and vector Laplace-Gauss beams," Opt. Lett., **30**, 2155 (2005)

Manipulación de haces vHzG

$$\mathbf{e}_1(\mathbf{r}_1) = \exp\left(\frac{iKr_1^2}{2q_1}\right) \nabla_1 W(\mathbf{r}_1; \kappa_1), \quad \mathbf{h}_1(\mathbf{r}_1) = \left(\frac{\varepsilon}{\mu}\right)^{1/2} \hat{\mathbf{z}} \times \mathbf{e}_1(\mathbf{r}_1),$$

$$\mathbf{e}_2(\mathbf{r}_2) = \frac{\kappa_1}{\kappa_2} \exp\left(-i\frac{\kappa_1 \kappa_2 B}{2K}\right) G(\mathbf{r}_2, q_2) \nabla_2 W(\mathbf{r}_2; \kappa_2),$$

$$\mathbf{h}_2(\mathbf{r}_2) = \left(\frac{\varepsilon}{\mu}\right)^{1/2} \hat{\mathbf{z}} \times \mathbf{e}_2(\mathbf{r}_2),$$



¿Preguntas ?



<http://optica.mty.itesm.mx/pmog>