Directivity of sub-wavelength wire lasers

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Acknowledgements:

Experimental investigation of the far field of THz cascade lasers:

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THz cascade lasers:

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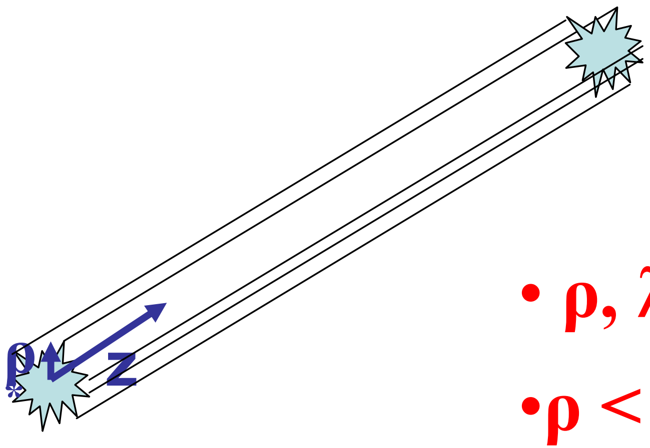
Wire lasers



- ρ, $\lambda \ll L$;
- $\rho < \lambda$
- uniform or periodic along z direction with period $\ll \lambda$;

High directivity laser with subwavelength aperture.

Is it possible?

Methods used to improve directivity of lasers with small transverse dimensions

- External optics (lenses, horn antennas)

- Emission is coupled out though the substrate

-Emission from the surface parallel to active layer (grating on top of the structure)

Zh. I. Alferov, V. M. Andreev, S. A. Gurevich R. F., Kazarinov, V. R. Larionov, M. N. Mizerov, and E. L., Portnoy, IEEE J. Quant. Electron. QE-11, 449 (1975).

- A set of lasers as a phased array

Effective aperture is enlarged

High directivity laser with subwavelength aperture - what for?

Small aperture

+

Low divergency

Local laser excitation for applications in biology, medicine, effective coupling of THz QC lasers, lasers with higher frequencies - applications in optical memory, quantum information etc.

“Every day more joy to live!”

Local laser excitation for applications in iology, medicine, ffective coupling f THz QC lasers, sers with higher frequencies - applications in ptical memory, quantum information etc.

However!

Diffraction limit:

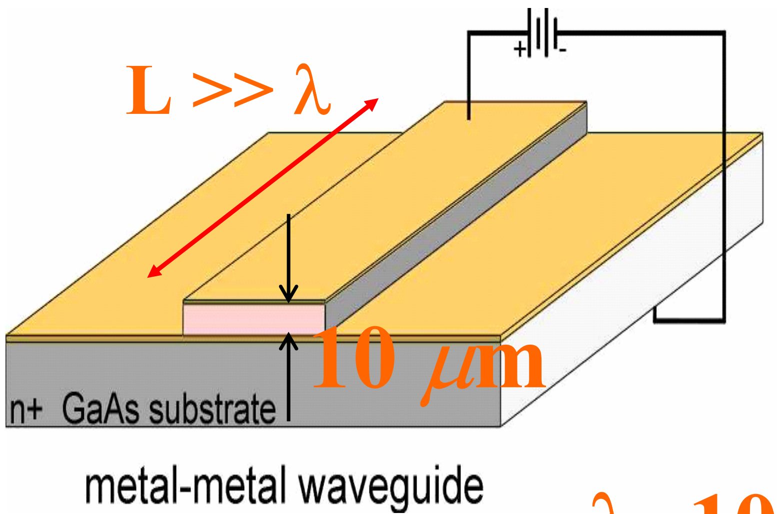
$a > \lambda$ $\sin\theta \approx \lambda/a$

wavelength

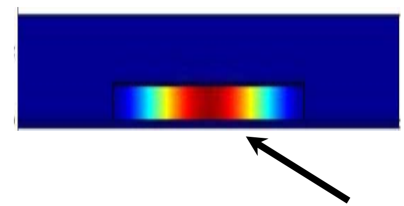
Aperture size

What happens when $\mathbf{a} < \boldsymbol{\lambda}$ **?**

Waveguide of the THz quantum cascade laser

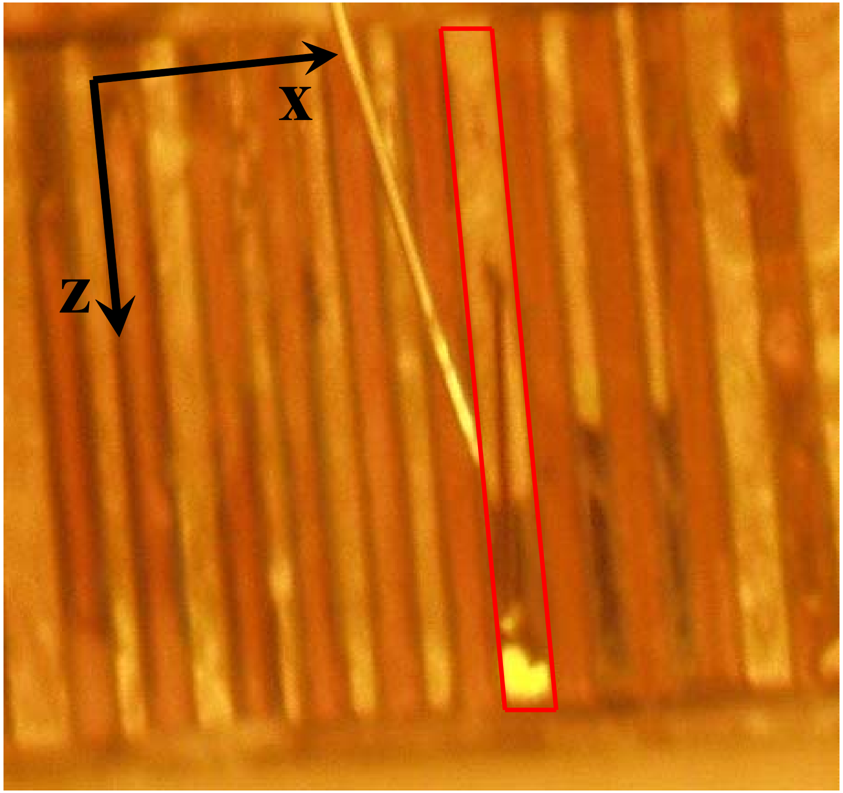


$\lambda \approx 100 \mu m$



MIT, Sandia, 2003

Structure view

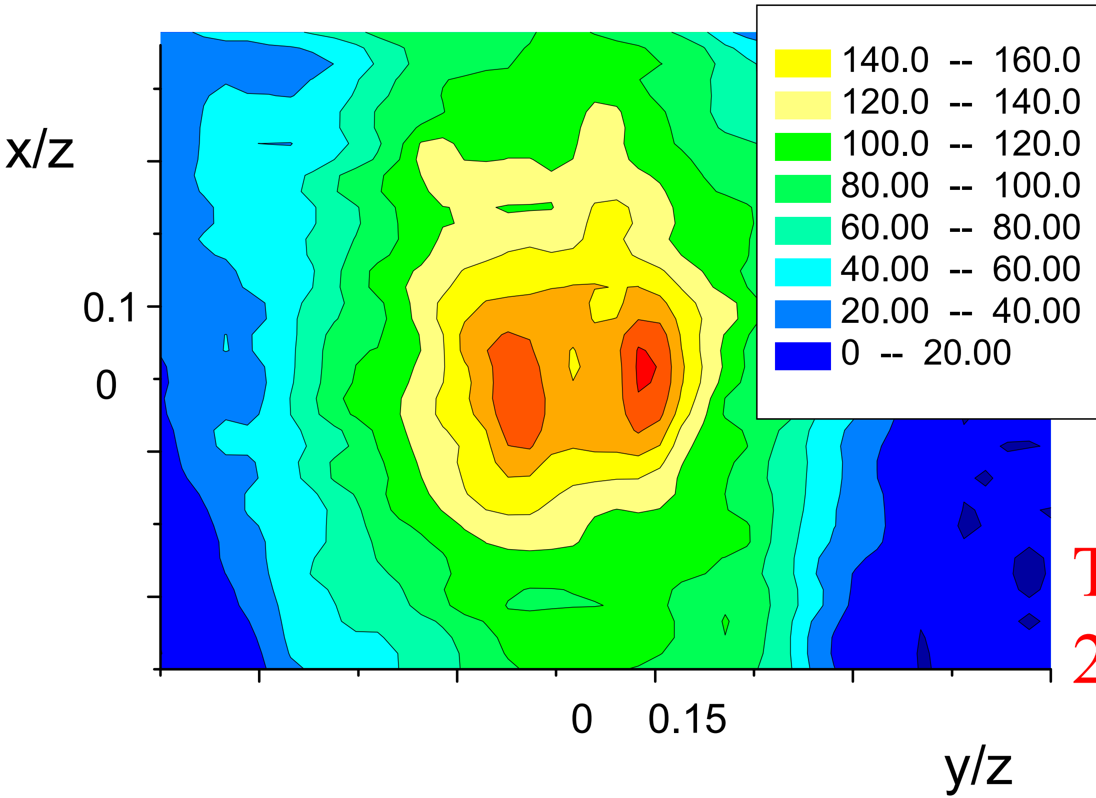


z: L=1180μm.

x: a=40μm

y: h=10μm

First result: narrow maximum in the far field of quantum cascade laser 1180/40/10 μm, λ≈100 μm, θ < 0.1 π



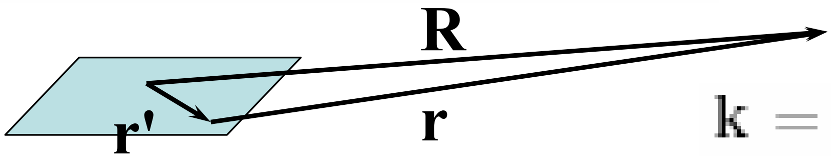
TU Delft
2004

Equivalent currents approach:

Far field is expressed in terms of equivalent current produced by the laser mode within the laser medium with ε ≠ 1:

$$\boxed{\mathbf{J}_{eq} = \mathbf{J}_c + \frac{j\omega(\varepsilon - 1)}{4\pi}\mathbf{E},}$$

$$\mathbf{A} = \frac{1}{c}\int_v \mathbf{J}_{eq}\frac{\exp(-jkr)}{r}dV, \qquad \mathbf{E} = -\frac{j\omega}{c}\mathbf{A} + \frac{c}{j\omega}\nabla(\nabla\mathbf{A})$$



Far Field Zone:

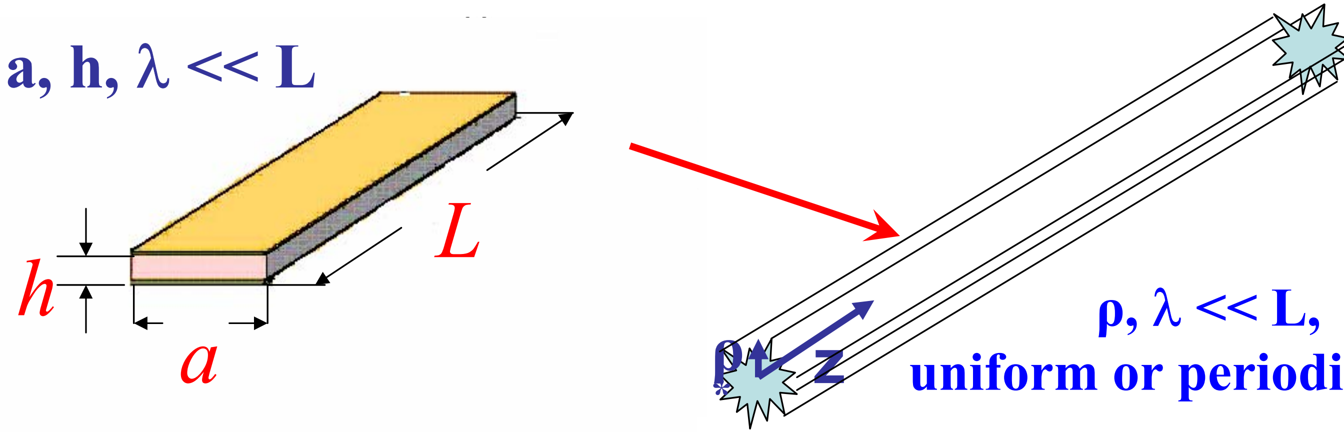
$$\mathbf{k} = k\mathbf{R}/R \qquad kr \simeq kR - \mathbf{k}\mathbf{r}'$$

$$\boxed{\mathbf{E} = -\frac{j\omega}{c^2}\frac{\exp(-jkR)}{R}\sum_i \mathbf{E}_i \int_V J^i_{eq}\exp(j\mathbf{k}\mathbf{r}')d\mathbf{r}'}$$

$\mathbf{E}_\mathbf{i}$ – polarization factor

$$\mathbf{E}_i = \mathbf{x}_0^i - \mathbf{r}_0(\mathbf{x}_0^i\mathbf{r}_0) \quad \mathbf{r}_0 = \mathbf{R}/R$$

Wire model of laser mode structure



ρ, λ << L,
uniform or periodic along z direction: G << λ

Exact solution for L →∞ - Bloch functions:

$$\boxed{J^i_{eq} = \tilde{J}^i(\rho, z)(\exp(jqz) \pm \exp(-jqz))}$$

Boundary conditions at $|z|=L/2$ → Discrete spectrum of ω

→ Edge effects are neglected (L >> a, L >> λ)

Far field of wire laser

$$J^i_{eq} = \tilde{J}^i(\rho, z)(\exp(jqz) \pm \exp(-jqz))$$

$$\mathbf{E} = -\frac{j\omega}{c^2}\frac{\exp(-jkR)}{R}\sum_i \mathbf{E}_i \int_V J^i_{eq}\exp(j\mathbf{k}\mathbf{r}')\mathrm{d}\mathbf{r}'$$

Transverse and longitudinal integrals factor out

$$\mathbf{E} = -\frac{j\omega}{c^2}\frac{\exp(-jkR)}{R}L\sum_i \mathbf{E}_i F_i^{\perp} F_i^z$$

Transverse factor

$$F_i^{\perp} = \int_S \tilde{J}^i(\rho)\exp(j\mathbf{k}_{\perp}\rho)\mathrm{d}\rho$$

Longitudinal factor

$$F_i^z = \int \exp(j\mathbf{k}_z z)(\exp(jqz) \pm \exp(-jqz))\mathrm{d}z$$

Transverse factor

This term is analogous to that of aperture methods of far field calculation

$$F_i^{\perp} = \int_S \bar{J}^i(\rho)\exp(j\mathbf{k}_\perp \rho)\mathrm{d}\rho$$

a > λ

$$\Theta \simeq \lambda/a$$

a < λ

Exponential term is expressed as a series of a/λ → weak angular dependence

Longitudinal factor

φ - phase difference of radiation from sources along the laser

$$F_i^z = \frac{\sin(\varphi_+)}{\varphi_+} \mp \frac{\sin(\varphi_-)}{\varphi_-},$$

$$\varphi_\pm = (q \pm k_z)L/2$$

$$\varphi_\pm = (c/c_L \pm \cos(\theta))\pi L/\lambda$$

maxima: $|\varphi_\pm| = |(c/c_L \pm \cos(\theta))\pi L/\lambda| = 0, (n+1/2)\pi$

q- longitudinal wave vector of the mode

q > k (c>c_L)

Cone-like maxima,

$$\cos(\theta + d\theta) - \cos(\theta) = \lambda/L$$

phase difference is nonzero in all directions

q = k (c=c_L)

Narrow beam along the longitudinal axis

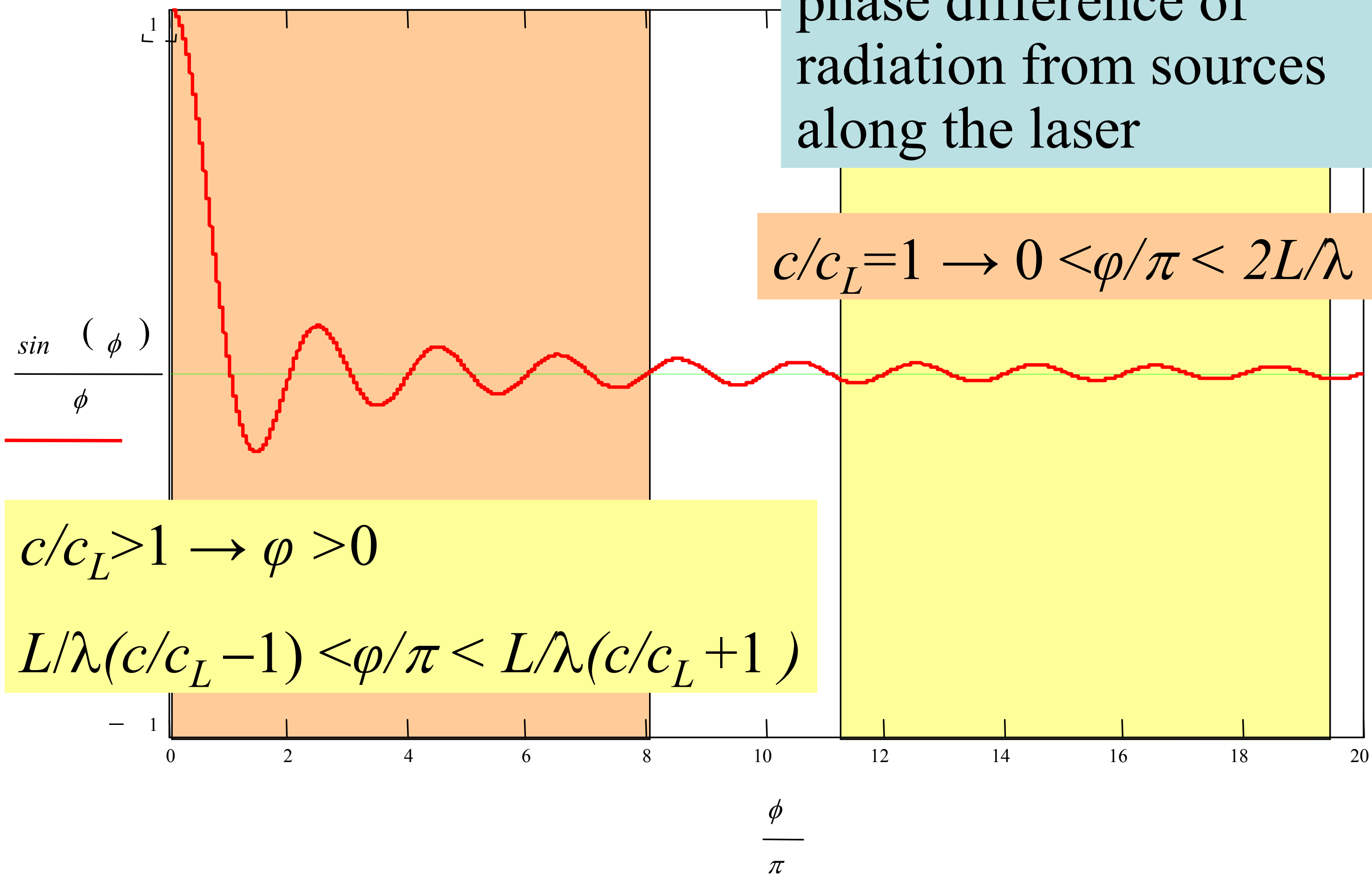
$$\Theta \simeq \sqrt{\lambda/L}$$

$\Theta = 0$ direction of zero phase difference

Sin(φ)/φ

$\varphi = \pi L/\lambda (c/c_L - \cos(\theta))$

phase difference of radiation from sources along the laser



$c/c_L = 1 \rightarrow 0 < \varphi/\pi < 2L/\lambda$

$c/c_L > 1 \rightarrow \varphi > 0$

$L/\lambda(c/c_L - 1) < \varphi/\pi < L/\lambda(c/c_L + 1)$

Sinchronouse modes – narrow beam:

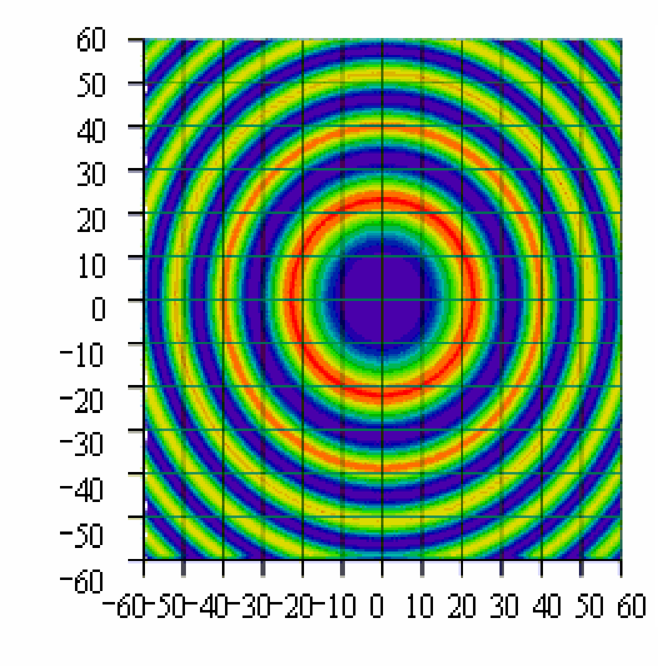
$$\boxed{L \gg a,\ L \gg \lambda,\ a < \lambda,\ q = k\ (c = c_L)}$$

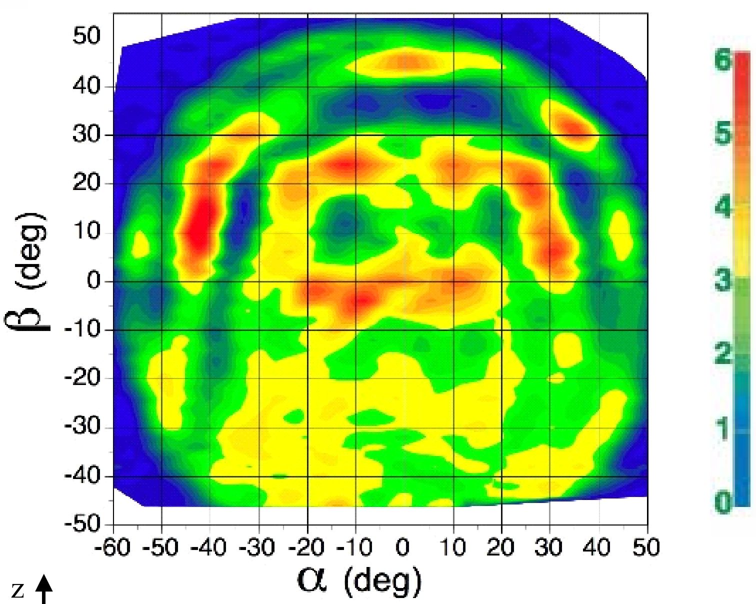
$$\boxed{\Theta \simeq \sqrt{\lambda / L}}$$

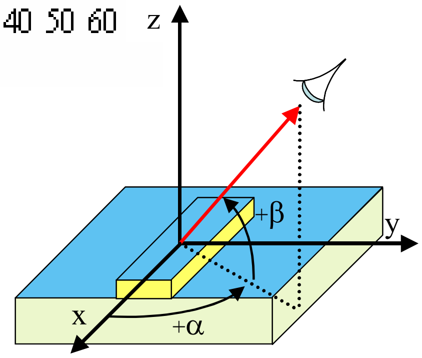
When $N_F = a^2/2\lambda L \ll 1$

$\Theta \ll \lambda/a$

Theory/experiment for q > k



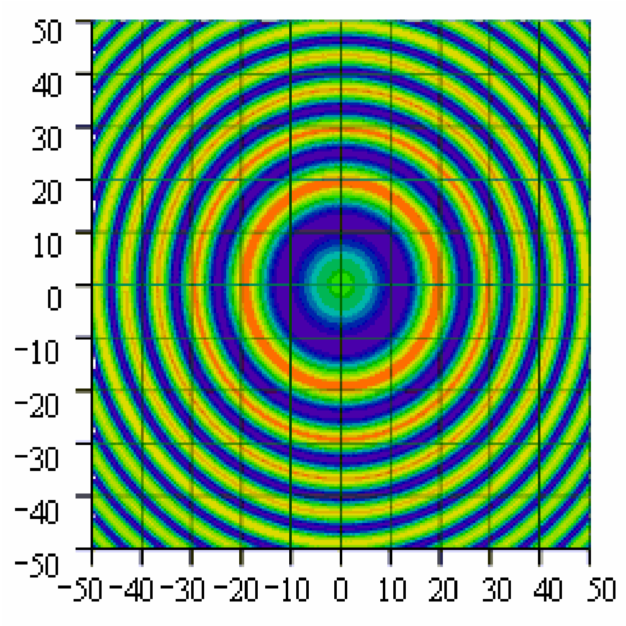


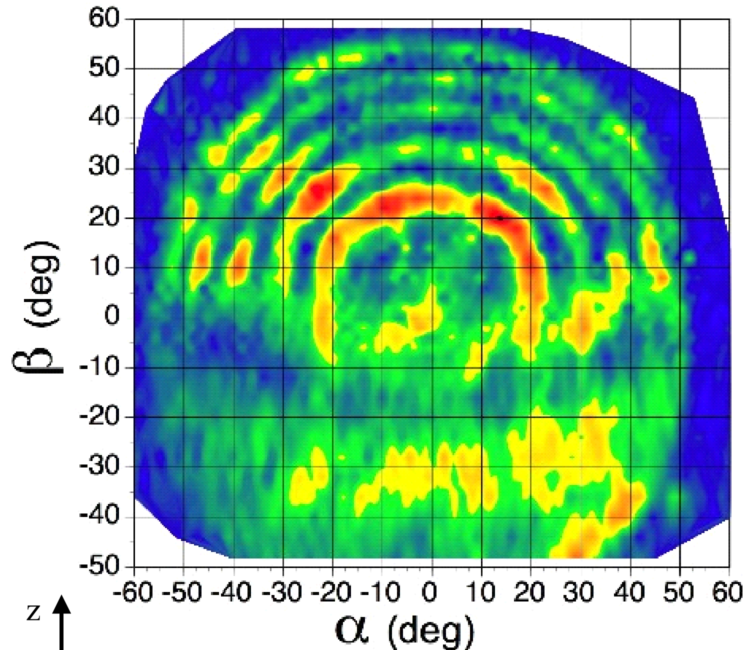


L=670 μm,

λ = 102.7 μm

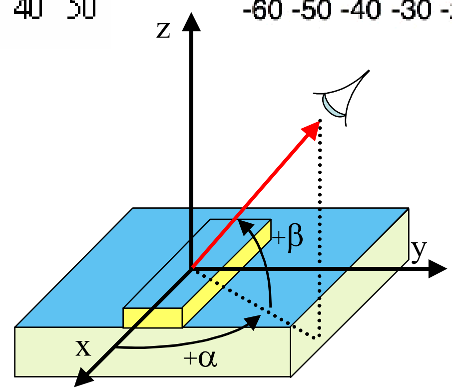
Theory/experiment for q > k





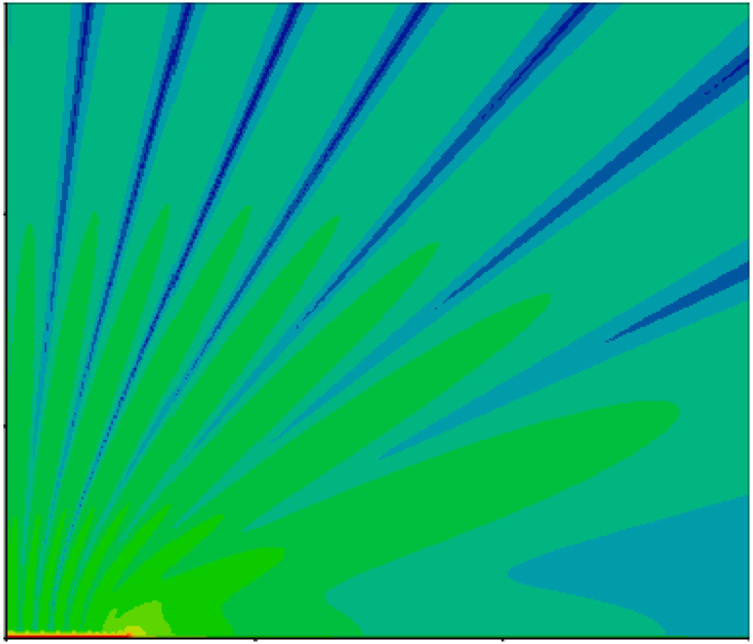
L=1500 μm,

λ = 109.1 μm

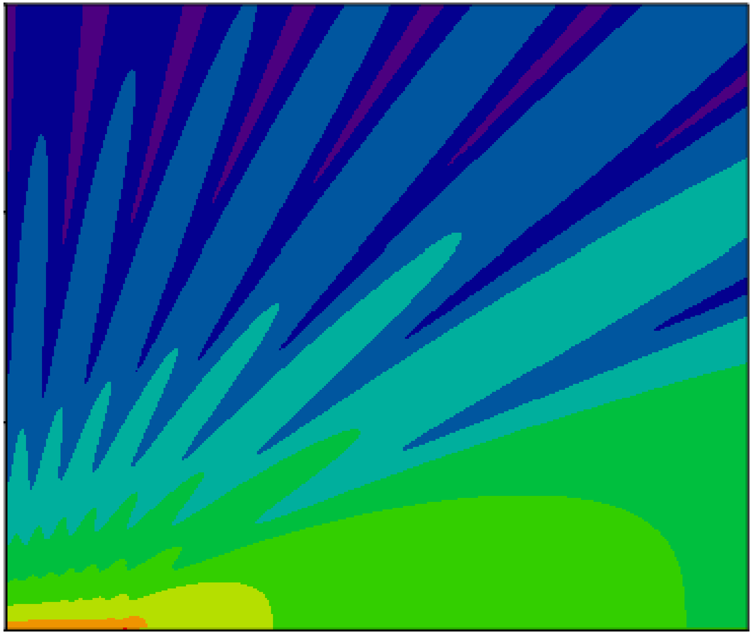


Far and near field
of infinitely thin wire laser

$q > k$ "cabbage"



$q = k$: "flower bulb"



Conditions of realization for syncrhonized modes $q = k$ ($c=c_L$)

~~Grating with period $2\pi/k$?~~

Disperion relation inside laser medium: $q^2 = k^2 n^2 - k_{\perp}^2$

Longitudinal wave vector can be changed by changing transverse parameters of the structure

Properties of synchronized modes $q = k$ ($c=c_L$)

Dispersion relation: $k_\perp^2 = q^2 - k^2 = 0$

- no exponential decay outside laser medium

Transverse field distribution is described by quasi-static equation: $\Delta_\perp \Pi = 0$

Power decay is determined by system geometry:

Cylinder monopole –

$E \sim 1/\rho \rightarrow \rho(P=P_t/2)=\infty$ **effective aperture for infinite wire is infinite**

Cylinder dipole –

$E \sim 1/\rho^2 \rightarrow \rho(P=P_t/2)=\sqrt{2}a$ **effective aperture is subwavelength**

Conclusions:

- Far field of subwavelength wire lasers

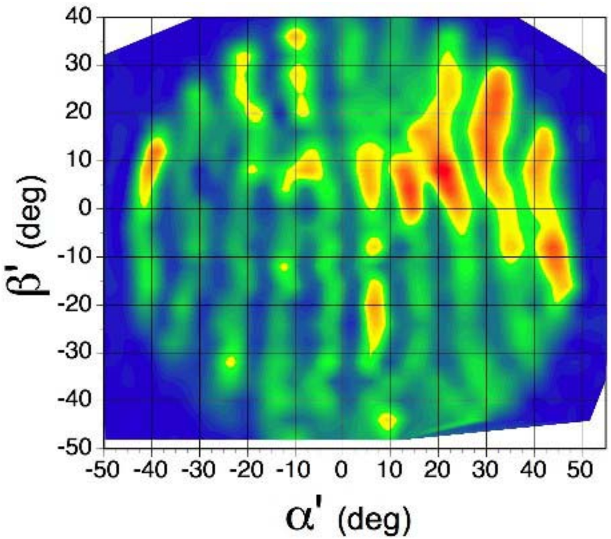
  L >> a ***L >>*** λ **a <** λ

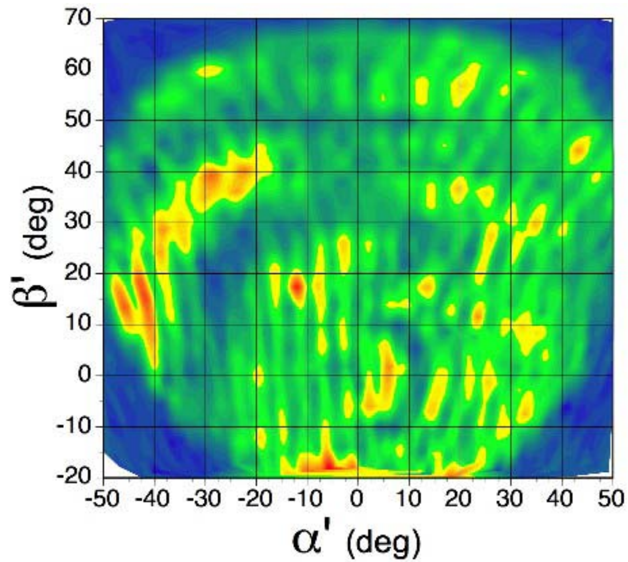
  is determined by interference of radiation from longitudinal mode distribution
- High directivity can be achieved from the modes of subwavelength laser at synchronism of longitudinal phase velocity with that of light with beam width :

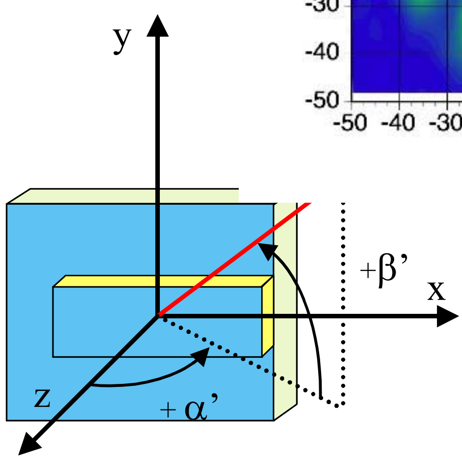
$$\Theta \simeq \sqrt{\lambda/L}$$

- Synchronous modes have relatively low confinement; realization of narrow beam emission from synchronous modes requires mode selection for single mode generation

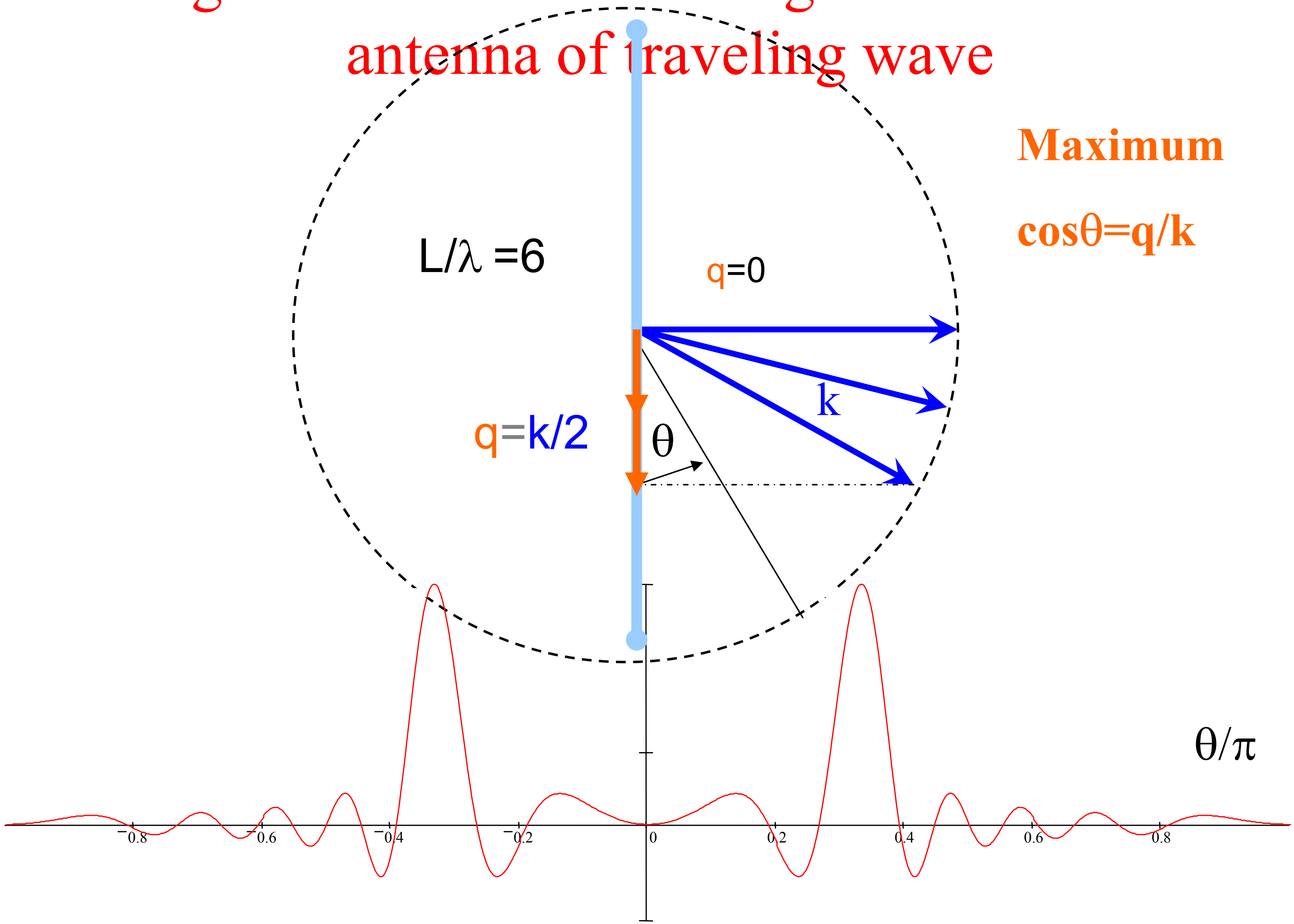
Emission in the plane parallel to the axis



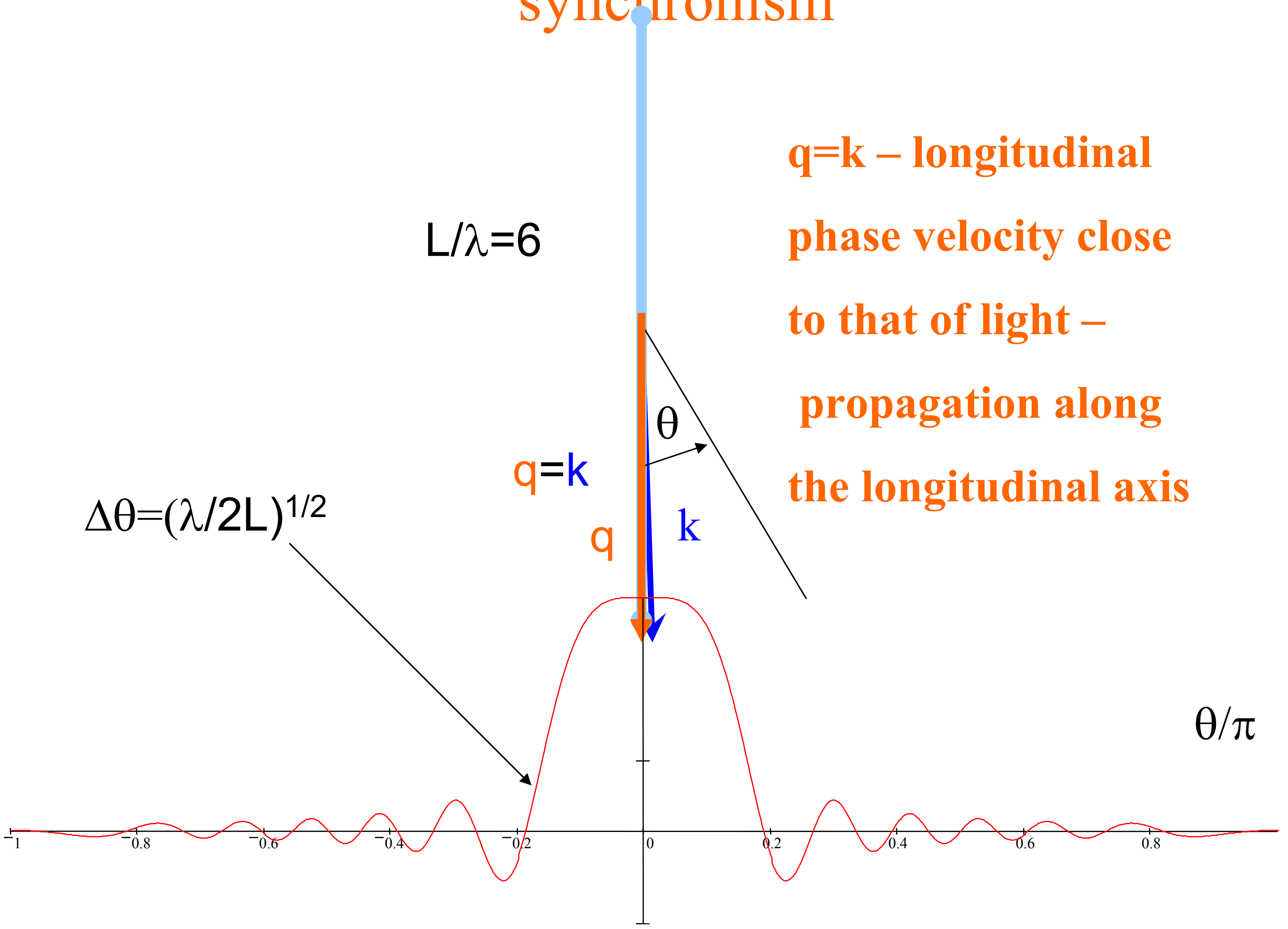




Longitudinal factor is analogous to far field of antenna of traveling wave

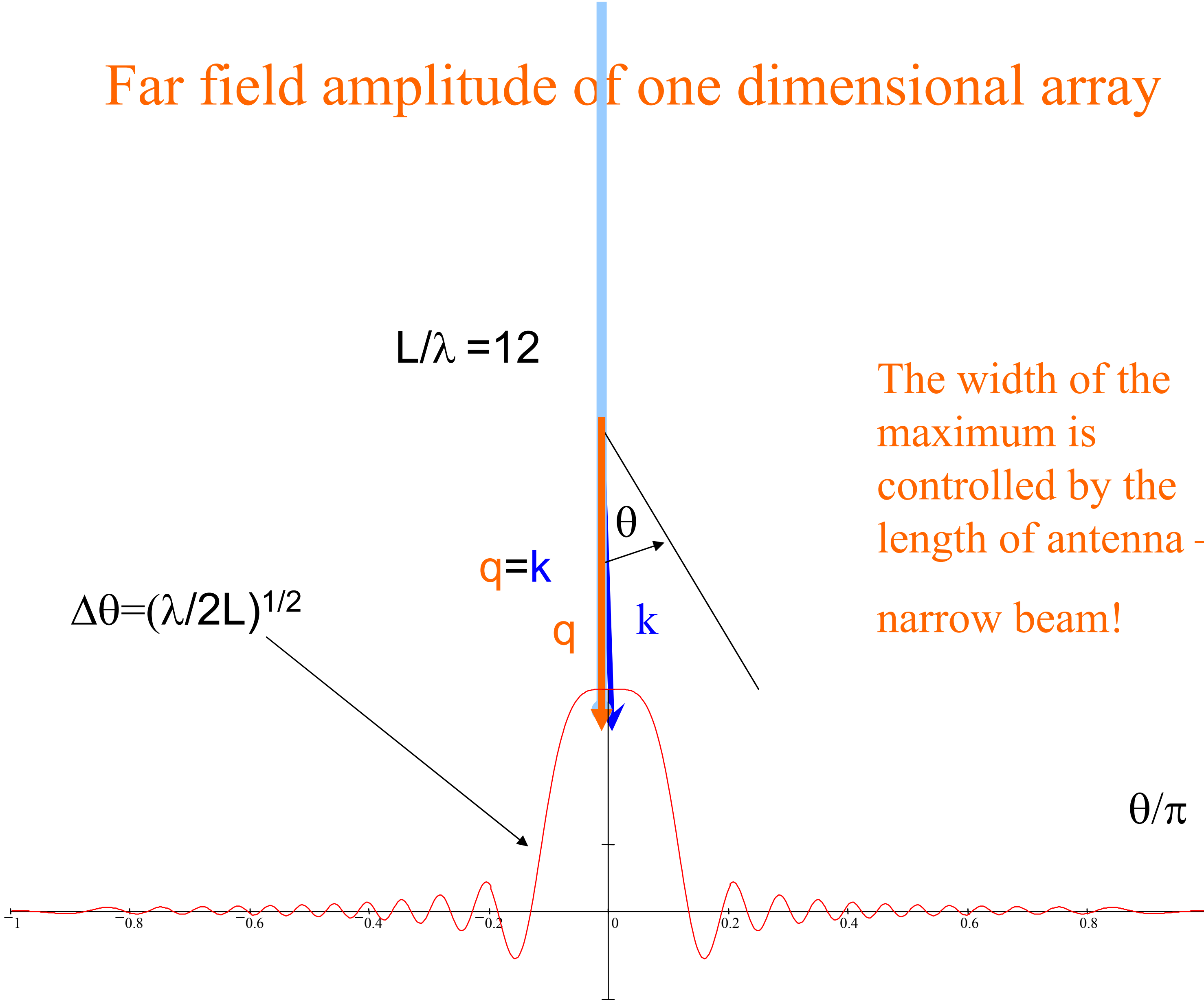


Far field of travelling wave antenna at phase synchronism



q=k – longitudinal phase velocity close to that of light – propagation along the longitudinal axis

Far field amplitude of one dimensional array



The width of the maximum is controlled by the length of antenna –

narrow beam!

Far field amplitude of one dimensional array