Principles of Lasers

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Chapter 5

Passive Optical Resonators

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Chapter 5_L14

- Stable resonators

Stable resonator

- Assume the resonator has infinite aperture, at the initial plane z_1=0, the electric field is E(x1,y1,0)=u(x1,y1,0)exp(-j0). Then, after one round trip at z=2L plane, the electric field becomes is E(x,y,0)=u(x,y,2L)exp(-j2kL). Again, the F-K relation gives

$$\boxed{E(x,y,2L)=\frac{j}{B\lambda}\exp(-2jkL)\times\int\int_{-\infty}^{\infty}E(x_1,y_1,0)\exp\left(-jk\frac{A\left(x^2+x_1^{\,2}\right)-2x_1x+D\left(y^2+y_1^{\,2}\right)-2y_1y}{2B}\right)dx_1dy_1}$$

- Then, the propagation Kernel is given by

$$\boxed{K(x,y,x_1,y_1)=\frac{j}{B\lambda}\exp\left(-jk\frac{A\left(x^2+x_1^{\,2}\right)-2x_1x+D\left(y^2+y_1^{\,2}\right)-2y_1y}{2B}\right)}$$

- We already know the solution of K-F equation is Gaussian, Hermite-Gaussian or Laguerre-Gaussian beam for infinite apertures.

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Stable resonator

- For the cavity eigenmodes, it requires that the beam reproduces itself after one round trip, that is, if the initial q parameter is q_1, the q parameter q afer one round trip must equal to q_1. That is,

$$\boxed{q = \frac{Aq+B}{Cq+D} = q_1}$$

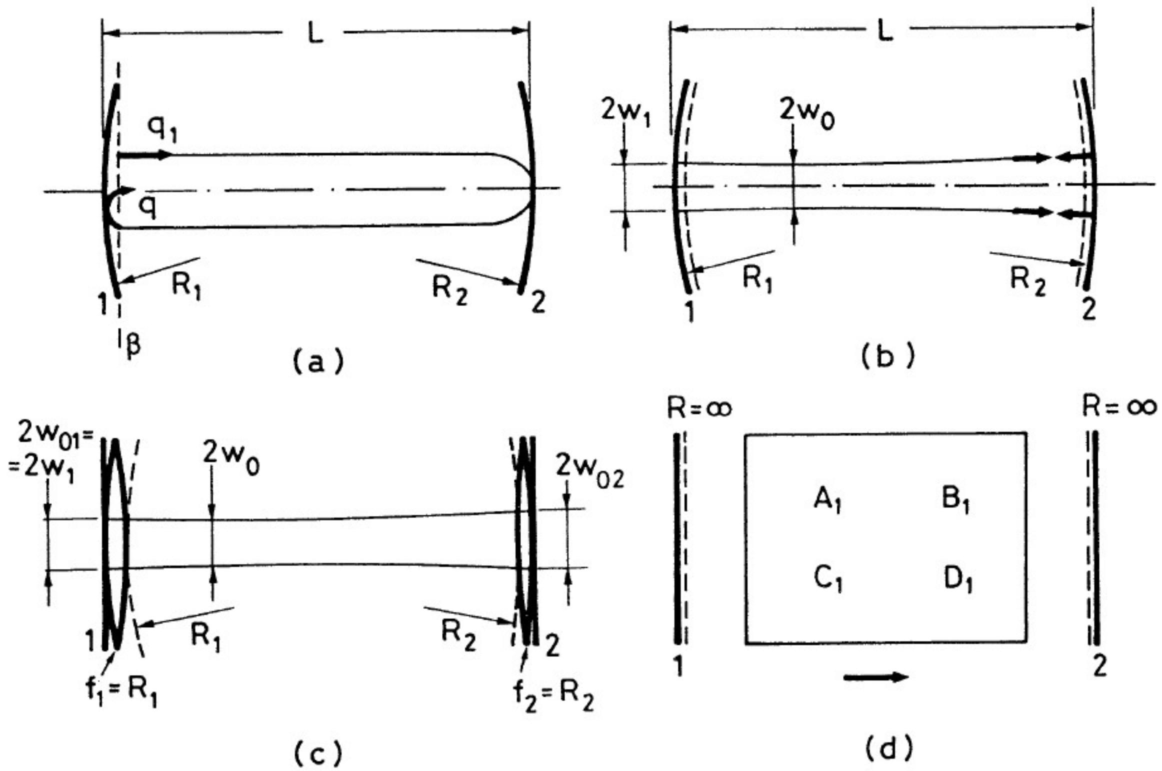
- Then, we obtain,

$$Cq^2 + (D-A)q - B = 0$$
$$\text{q is complex number} \Rightarrow$$
$$(D-A)^2 + 4BC < 0$$
$$AD - BC = 1 \Rightarrow$$
$$-1 < \frac{A+D}{2} < 1$$

- This means that a Gaussian beam solution can only be found for stable resonators, or that all stable resonators with infinite aperture have modes by Gaussian, Hermite-Gaussian or Laguerre-Gaussian solutions.

Eigenmodes in stable resonator

- To caluclate the electric field distribution in the stable resonator, we only need to know the q parameter of the Guasian-X beams.
- The spherical mirror R1, R2 cavity is equivalent to the following cavity formed by a combination of plan mirrors with thin lens of $f_1=R_1$, $f_2=R_2$.



Eigenmodes in stable resonator

- The round-trip matrix is obtained from the two plane mirrors and the other optical elements of single-pass matrix $A_1B_1C_1D_1$.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} D_1 & B_1 \\ C_1 & A_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}$$

$$= \begin{bmatrix} 2A_1D_1 - 1 & 2B_1D_1 \\ 2A_1C_1 & 2A_1D_1 - 1 \end{bmatrix}$$

- The q paprameter after one round trip is

$$Cq^2 + (D - A)q - B = 0$$

$$\text{A=D} \Rightarrow$$

$$Cq^2 - B = 0 \Rightarrow$$

$$\text{q=q}_1 = j\sqrt{-\frac{B}{C}} = j\sqrt{-\frac{B_1D_1}{A_1C_1}}$$

$$\text{Similarly } \text{q}_2 = j\sqrt{-\frac{A_1B_1}{C_1D_1}}$$

- q1 and q2 are purely imaginary values because BC<0, indicates the equiphase surface on the plane mirrors are plane (c), or on the spherical mirrors (b) are spherical with the the same curvature.

Eigenmodes in stable resonator

- A general conclusion is that in stable resonators, the wavefront (equiphase surface) at the cavity mirror always coincides with the mirror surface. That is, the curvature of the beam at the mirror is the same at the curvature of the mirror. Thus, the propagating rays at the mirror must be orthogonal to the mirror surface.

- The single-pass matrix $A_1B_1C_1D_1$in (c) is

$$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_1} & 1 \end{bmatrix} = \begin{bmatrix} g_1 & L \\ -\dfrac{1-g_1g_2}{L} & g_2 \end{bmatrix}$$

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Eigenmodes in stable resonator

- From the q parameter, we can obtain the beam spot size on the mirrors in (b),

$$W_1 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{g_2}{g_1(1-g_1g_2)}\right)^{1/4}\ ;\ W_2 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{g_1}{g_2(1-g_1g_2)}\right)^{1/4}$$

$$g_1 = 1-\frac{L}{R_1}$$
$$g_2 = 1-\frac{L}{R_2}$$

- The beam waist size and position inside the cavity (using pp. 157) is

$$W_0 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{g_1g_2(1-g_1g_2)}{(g_1+g_2-2g_1g_2)^2}\right)^{1/4}$$
$$z = R_1/[1+(R_1/z_{R1})^2];\ z_{R1} = \pi W_0^2/\lambda$$

- For a symmetric resonator $R_1=R_2=R$

$$W = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{1}{1-g^2}\right)^{1/4}$$
$$W_0 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{1+g}{4(1-g)}\right)^{1/4}$$
$$z = L/2$$

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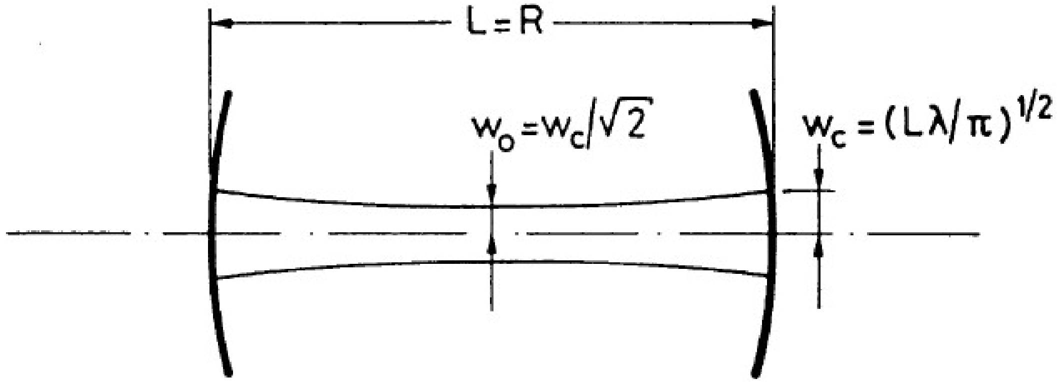
Eigenmodes in confocal cavity

- The g parameter for confocal cavity is g=0



(a)

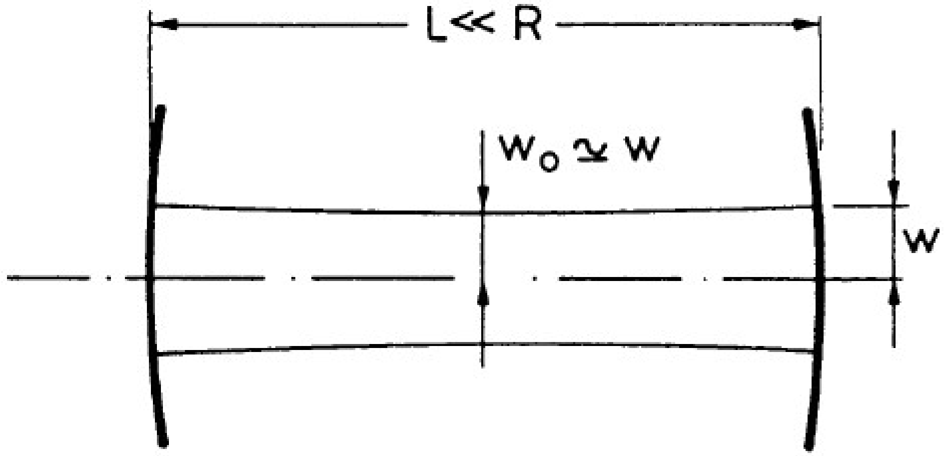
- The beam spot size at the mirror and the beam spot size are

$$W = \left(\frac{L\lambda}{\pi}\right)^{1/2}$$

$$W_0 = \left(\frac{L\lambda}{2\pi}\right)^{1/2} = \frac{W}{\sqrt{2}}$$

Eigenmodes in near-plane resonator

- In near-plane cavity, R>>L, g=1-epsilon, and epsilon is small &positive



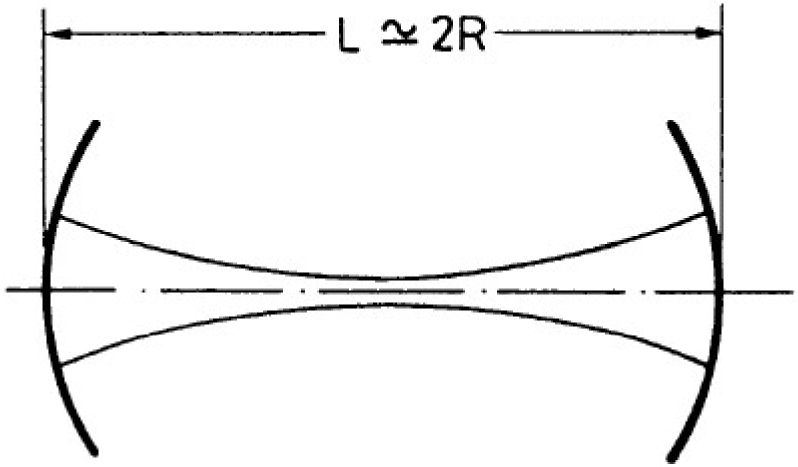
$$W = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{1}{2\varepsilon}\right)^{1/4}$$

$$W_0 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{1}{2\varepsilon}\right)^{1/4} = W$$

That is, the beam waist size is similar to the beam size at mirrors.

Eigenmodes in near-concentric cavity

- In near-concentric cavity, L~2R, g=-1+epsilon, and epsilon is small &positive



(c)

$$W = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{1}{2\varepsilon}\right)^{1/4}$$

$$W_0 = \left(\frac{L\lambda}{\pi}\right)^{1/2}\left(\frac{\varepsilon}{8}\right)^{1/4}$$

That is, the beam waist size is very small.

- Note that beam size at mirrors of every cavity is usually less than 1 mm.

Examples 5.5

Eigenvalues in stable resonator

- Based on the ABCD law of G-H beam, and the self-reproducing requirement in one round trip q=q1, we obtain the eigenvalues,

$$\boxed{u_{lm}(x_1, y_1, z_1) = H_l\left(\frac{\sqrt{2}x_1}{W_1}\right)H_m\left(\frac{\sqrt{2}y_1}{W_1}\right)\exp\left(-jk\frac{x_1^{\,2}+y_1^{\,2}}{2q_1}\right)}$$

$$\boxed{u_{lm}(x, y, z) = \left[\frac{1}{A+B/q_1}\right]^{1+l+m} H_l\left(\frac{\sqrt{2}x}{W}\right)H_m\left(\frac{\sqrt{2}y}{W}\right)\exp\left(-jk\frac{x^2+y^2}{2q}\right)}$$

$$\boxed{\begin{aligned} &u(x, y, 2L) = \tilde{\sigma}u(x, y, 0) \Rightarrow \\ &\tilde{\sigma}_{lm} = \frac{1}{\left(A+B/q\right)^{1+l+m}} = \left|\tilde{\sigma}_{lm}\right|\exp(j\phi_{lm}) \end{aligned}}$$

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Eigenvalues in stable resonator

Introduce $\sigma = A + B/q$

Then, $\tilde{\sigma}_{lm} = \dfrac{1}{\sigma^{1+l+m}}$

- The amplitude of the eigenvalue

The amplitude part of σ

$$|A + B/q|^2 = A^2 - BC$$

$$= AD - BC = 1 \Rightarrow$$

$$|\sigma|^2 = |\tilde{\sigma}_{lm}|^2 = 1 \Rightarrow$$

Because infinite mirror size has no (diffraction) loss

$$q = j\sqrt{-\frac{B}{C}} \Rightarrow$$

$$A + B/q = A - jB\sqrt{-\frac{C}{B}}$$

- Therefore,

$$\sigma = |\sigma| \exp(-j\phi) = \exp(-j\phi)$$

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Eigenvalue in stable resonator

- The phase of the eigenvalue

$$\sigma = \exp(-j\phi) = \cos\phi - j\sin\phi = A - jB\sqrt{-\frac{C}{B}}$$

The phase

$$\cos\varphi = A = 2A_1D_1 - 1$$

$$\phi_{lm} = -(1+l+m)\varphi = -(1+l+m)\cos^{-1}\left[\pm\left(2A_1D_1 - 1\right)\right]$$

- From the round-trip phase condition, the resonance frequency is obtained as

The resonance frequency

$$\nu_{lmn} = \frac{c}{2n_rL}\left[n + \frac{1+l+m}{\pi}\cos^{-1}\left(\pm\sqrt{A_1D_1}\right)\right]$$

For two-mirror resonator

$$\nu_{lmn} = \frac{c}{2n_rL}\left[n + \frac{1+l+m}{\pi}\cos^{-1}\left(\pm\sqrt{g_1g_2}\right)\right]$$

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Resonance frequency

- Resonance frequency of confocal resonator, g1=g2=0,

$$\boxed{\nu_{lmn} = \frac{c}{4n_r L}\left[2n + (1 + l + m)\right]}$$

- For the same longitudinal mode index n, the frequency spacing of transverse mode is

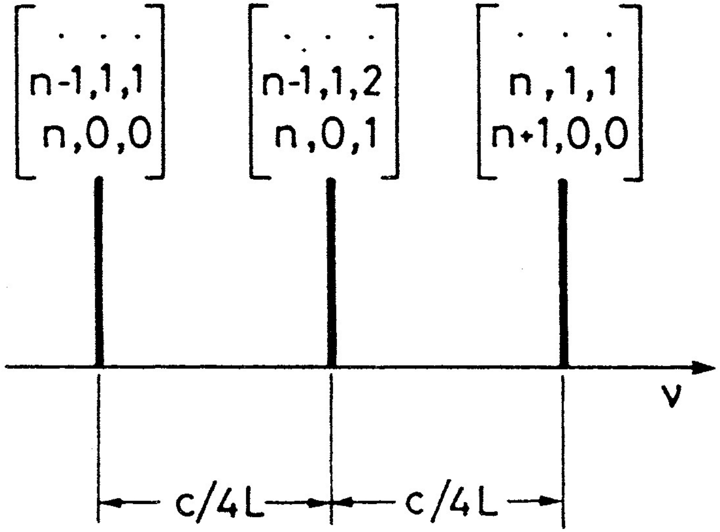
$$\boxed{\Delta\nu_{lm}\Big|_{\mathrm{n}=n0} = \frac{c}{4n_r L}}$$

- For the same transverse mode index (l,m), the frequency spacing of longitudinal mode is

$$\boxed{\Delta\nu_{n}\Big|_{l,m=l0,m0} = \frac{c}{2n_r L}}$$

- The consecutive mode spacing is

$$\boxed{\Delta\nu_{lmn} = \frac{c}{4n_r L}}$$

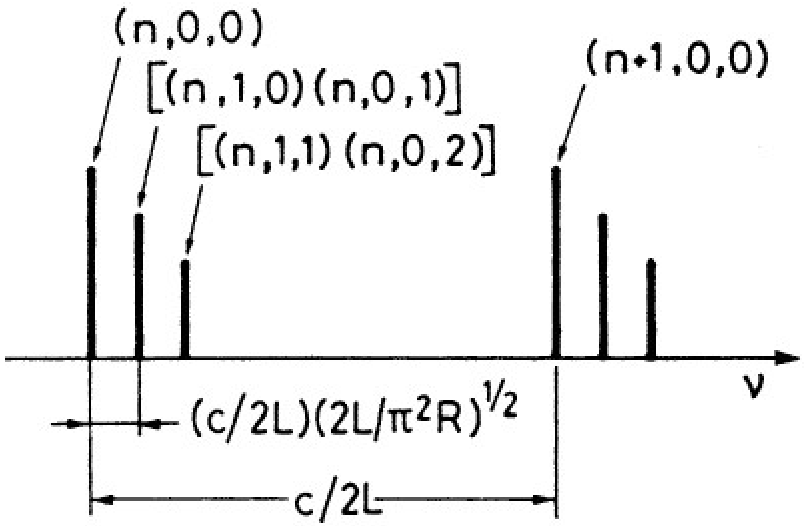


- Frequency degeneracy: Modes having the same value of 2n+l+m have the same resonance frequency, although they correspond to different spatial configurations.

Resonance frequency

- Resonance frequency of near-plane and symmetric resonators g1=g2=g=1-L/R, with L/R<<1.

$$\boxed{\nu_{lmn} = \frac{c}{2n_r L}\left[2n + \frac{(1+l+m)}{\pi}\sqrt{\frac{2L}{R}}\right]} \qquad \cos^{-1} g \approx \sqrt{2L/R}$$



Mode description

The usage of the terms "longitudinal mode" and "transverse mode" in the laser literature has sometimes been rather confusing, and can convey the (mistaken) impression that there are two distinct types of modes, viz., longitudinal modes (sometimes called axial modes) and transverse modes. In fact any mode is specified by three numbers, e.g., n, m, l of (5.5.24). The electric and magnetic fields of the modes are nearly perpendicular to the resonator axis. The variation of these fields in a transverse direction is specified by l, m while field variation in a longitudinal (i.e., axial) direction is specified by n. When one refers, rather loosely, to a (given) transverse mode, it means that one is considering a mode with given values for the transverse indices (l, m), regardless of the value of n. Accordingly a single transverse mode means a mode with a single value of the transverse indexes (l, m). A similar interpretation can be applied to the "longitudinal modes". Thus two consecutive longitudinal modes mean two modes with consecutive values of the longitudinal index n [i.e., n and $(n + 1)$ or $(n - 1)$.

See pp. 181 for mode explanations

The electric field in the cavity

- The electric field inside the cavity is

$$\boxed{\begin{aligned} E_{lmn}(x,y,z) = \left(\frac{W_0}{W}\right)^{1+l+m} & H_l\left(\frac{\sqrt{2}x}{W}\right) H_m\left(\frac{\sqrt{2}y}{W}\right)\exp\left(-\frac{x^2+y^2}{W^2}\right) \\ & \times \exp\left[-jk_{lmn}\frac{x^2+y^2}{2R}\right] \\ & \times \exp\left[j(1+l+m)\phi\right] \\ & \times \exp\left[-jk_{lmn}z\right] \end{aligned}}$$

- ✓ *l* is number of field nulls along the x direction
- ✓ *m* is the number of field nulls along the y direction
- ✓ *n* is the number of half wavelength of the standing wave

- The standing wave eigenmode is the sum of the the two traveling electric field along the positive and negative directions along z.

$$E_+ = A\exp(j\omega t);\ E_- = A\exp(-j\omega t)$$

$$E_s = A\cos(\omega t)$$

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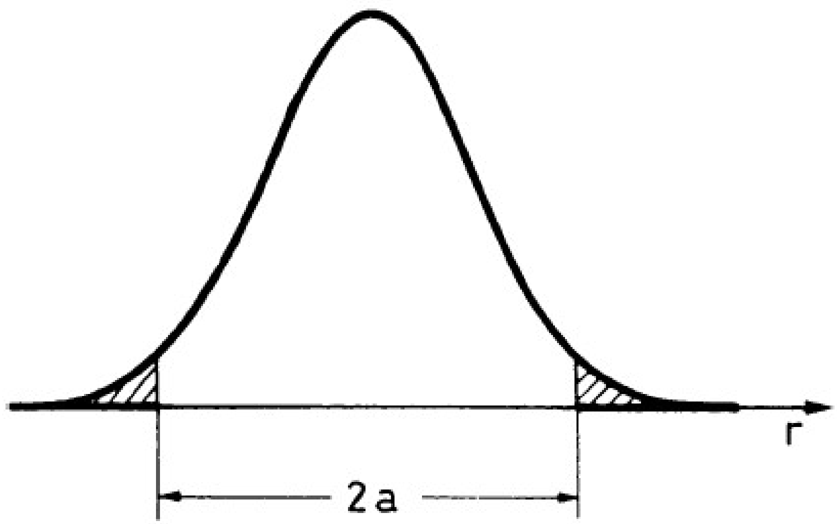
- Finite Aperture Effects

Finite aperture effects

- Infinite apertures of laser resonator has no diffraction loss, however, finite active medium size, mirror size and others leads to diffration loss.
- The finite aperture sizes significantly modifies the field distribution, which would no longer be precisely Gaussian shape.
- The exact solution resorts to the F-K integral equation.



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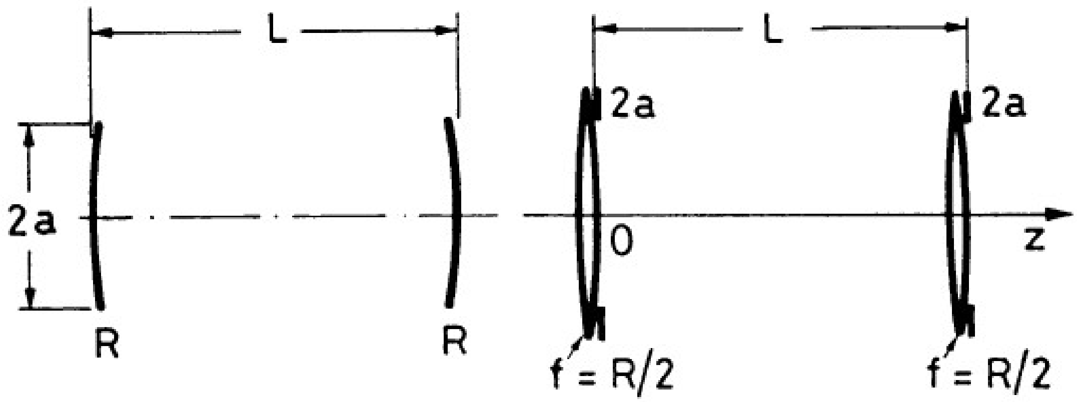
Finite aperture effects

- For a symmetric resonator with mirror radius of a and curvature of R, the electric field must reproduces its shape after one single pass.



- The integral equation becomes

$$\boxed{\tilde{\sigma}E(x,y,0)=\int_{-a}^{+a}\int_{-a}^{+a}K(x,y,x_1,y_1)E(x_1,y_1,0)dx_1dy_1}$$

$$\boxed{E(x,y,L)=\tilde{\sigma}E(x,y,0)\exp(-jkL)}$$

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Finite aperture effects

- The kernel K is determined by Eq. (5.5.1a) using the single-pass ABCD matrix,

$$\boxed{K(x,y,x_1,y_1)=\frac{j}{B\lambda}\exp\left(-jk\frac{A\left(x^2+x_1^{\ 2}\right)-2x_1x+D\left(y^2+y_1^{\ 2}\right)-2y_1y}{2B}\right)}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}\begin{bmatrix} 1 & \mathrm{L} \\ 0 & 1 \end{bmatrix}$$

- Note that the integration is from –a to a rather than infinite, thus the eigensolution is no longer the Hermite-Gaussian solutions.

Finite aperture effects

❑ The integration is usually solved by the **Fox-Li iterative procedure**, who first apply this procedure to obtain the eigenmodes of a Fabry-Perot resonator. The procedure is as follows:

1. Assume some field expression, say plane wave E(x,y,0) on the right hand
2. Employ the integral equation, calculate E(x,y,L) on the left hand
3. Insert E(x,y,L) to the right hand, and calculated E(x,y,2L) on the left hand
4. ……

$$
\begin{aligned}
&E(x,y,0) \Rightarrow E(x,y,L) \\
&E(x,y,L) \Rightarrow E(x,y,2L) \\
&\cdots \\
&E(x,y,nL) \Rightarrow E(x,y,(n+1)L)
\end{aligned}
$$

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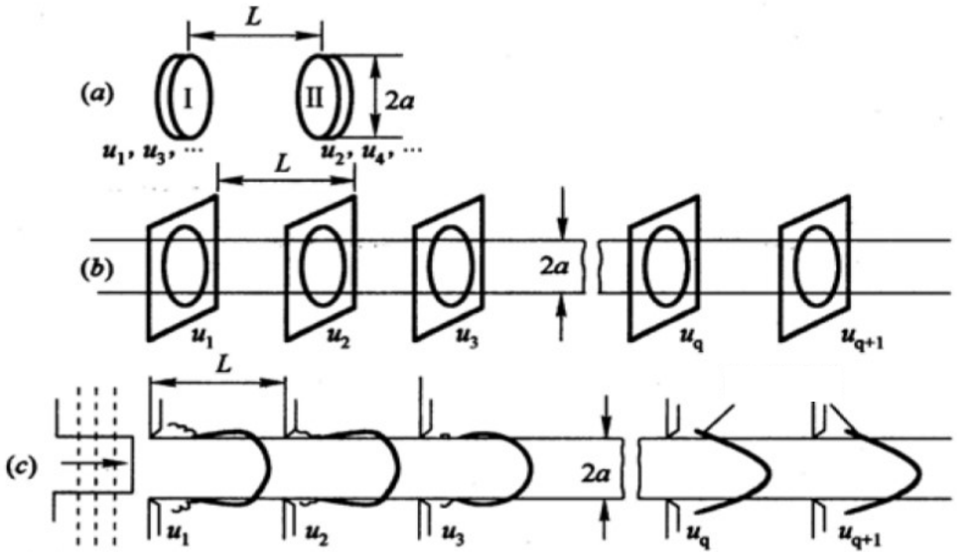
Finite aperture effects

- The procedure usually converges in a fez hundred iterations, eventually lead to a field which doesnot change any more on each successive iteration, except for an overall amplitude reduction dude to diffraction loss and a phase factor which accounts for the single-pass phase shift. In this way, one can compute the field amplitude distribution of the lowest order mode and also of higher order modes, as well as the corresponding diffraction losses and resonance frequencies.



Initial field is assumed to be a plane wave

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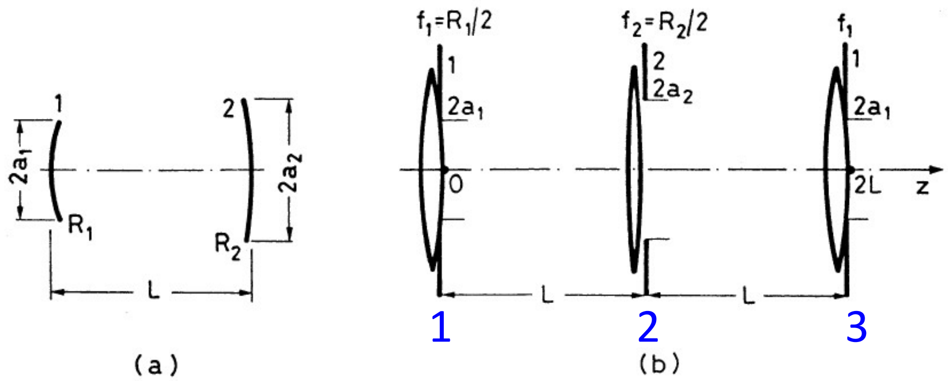
Finite aperture effects



- At z=0 plane, assume the field at the point (x_1,y_1) is $E(x_1,y_1,0)$, then the field $E(x_2,y_2,L)$ at the point (x_2,y_2) on z=L plane is

$$\boxed{E(x_2,y_2,L)=\exp(-jkL)\iint_1 K_{12}(x_2,y_2,x_1,y_1)E(x_1,y_1,0)dx_1dy_1}$$

- Similarly, the field $E(x_3,y_3,2L)$ at the point (x_3,y_3) on z=2L plane is

$$\boxed{E(x_3,y_3,2L)=\exp(-jkL)\iint_2 K_{21}(x_3,y_3,x_2,y_2)E(x_2,y_2,\mathrm{L})dx_2dy_2}$$

Finite aperture effects

- Therefore, the round-trip propagation of the electric field becomes

$$\boxed{E(x_3,y_3,2L)=\exp(-j2kL)\iint_2 K_{21}(x_3,y_3,x_2,y_2)dx_2dy_2\iint_1 K_{12}(x_2,y_2,x_1,y_1)E(x_1,y_1,0)dx_1dy_1}$$

- That is,

$$E(x_3,y_3,2L)=\exp(-j2kL)\iint_1 K(x_3,y_3,x_1,y_1)E(x_1,y_1,0)dx_1dy_1$$

The round-trip kernel

$$K(x_3,y_3,x_1,y_1)=)\iint_2 K_{21}(x_3,y_3,x_2,y_2)K_{12}(x_2,y_2,x_1,y_1)dx_2dy_2$$

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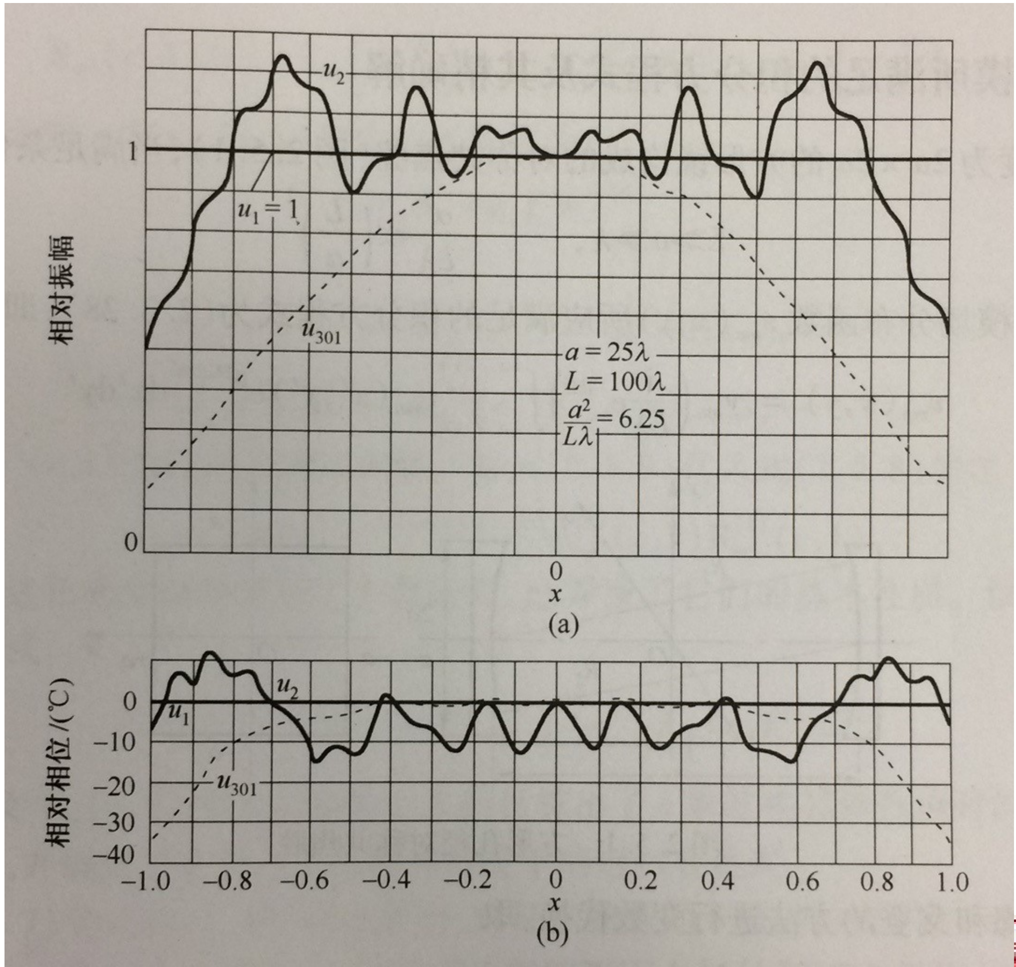
Finite aperture effects

- In a F-P cavity, assume the initial field is a plane wave with amplitude of 1 and phase of 0, the field distribution after 1 round trip and 301 round trip is as follows,



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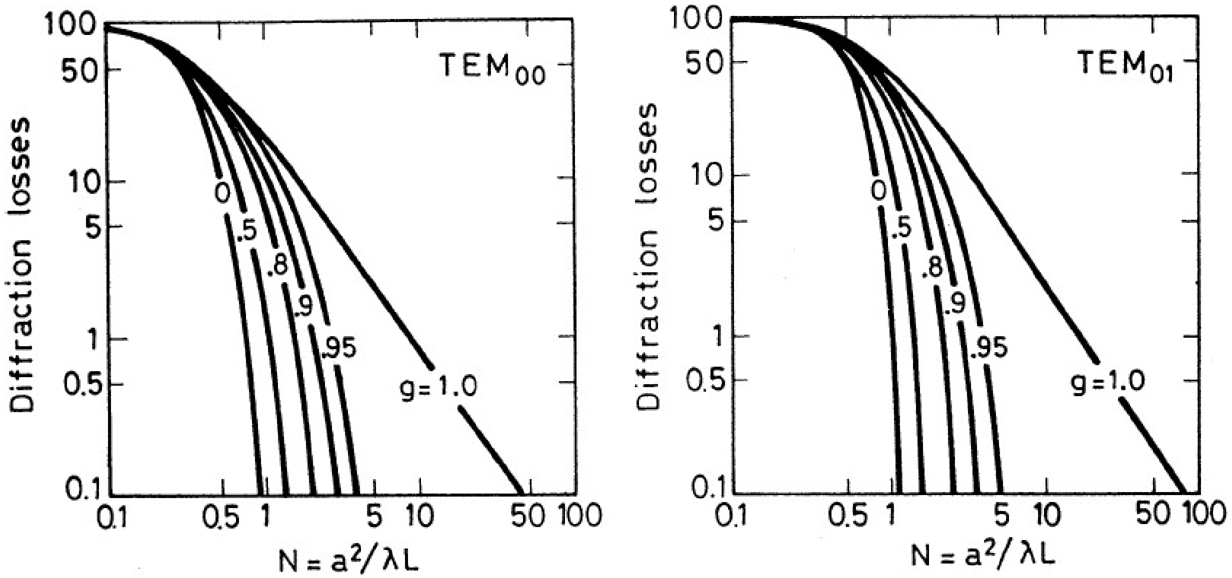
Finite aperture effects

- ❑ The diffraction loss decreases with the increasing Fresnel number
- ❑ For the same g parameter and the same Fresnel number, TEM00 mode has the lowest diffraction loss.



❑ **Fresnel number**

$$\boxed{N = \frac{a^2}{L\lambda}}$$

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- Unstable resonators

Unstable resonators

- In the g_1-g_2 plane, unstable resonators can be separated into two classes:

(1) positive branch resonators for $g_1g_2>1$

(2) Negative branch resonators for $g_1g_2<0$.

- The reason why unstable resonators are interesting:

In stable resonator,

(1) the beam size is usually on the order of the case for confocal resonator, which is usually less than 1 mm, because the beam is focused to the axis.

(2) In order to obtain TEM00 mode, the resonator aperture is limited to, say, 2mm.

(3) Therefore, the small beam volume limits the maximum available ouptut power.

In unstable resonator,

(1) It allows a large mode volume in a single transverse mode, because the field is not confined to the axis, and hence high power

(2) But is has much higher geometrical losses, and hence requires a high threshold.

Geometrical-optics description

- In the stable resonator, the amplitude of the eigenmodes is of Hermite-Gaussian form, and the phase is of the spherical wavefront. The presence of the Gaussian function limits the transverse size of the beam and essentially arises from the focusing properties of a stable spherical resonator.

- In the unstable resonator, there is no H-G solutions, so the beam is no longer focuses towar the resonator axis, but rather spread out over the whole resonator cross section.

- The eigensolution in unstable resonator approximately has a uniform amplitude amplitude over the resonator cross section, while the phase is still spherical wave front.
- The q parameter of unstable resonator is real, thus the eigenmode is indeed standing spherical waves, which is a superposition of two counter-propagating spherical waves.

$$Cq^2 + (D-A)q - B = 0$$

$$\text{Unstable: } (D-A)^2 + 4BC > 0 \Rightarrow$$

$$\text{q is real number}$$

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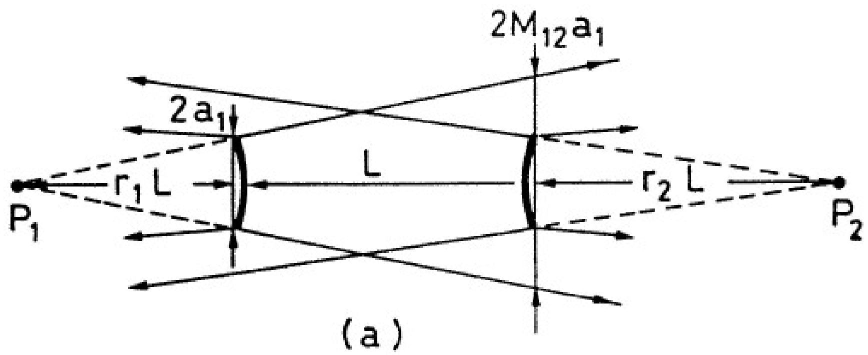
Geometrical-optics description

- To calculate the mode in the unstable resonator, let P1 and P2 be the centers of curvature of the two spherical waves.



- The self-production of eigenmodes requires that the spherical wave originating from point P1, after reflection at mirror 2, must give a spherical wave originating from P2, and vice versa.

Geometrical-optics description

- The positions of P1 and P2 are determined by the dimensionless quantities

$$\boxed{\begin{aligned} \frac{1}{r_1} &= g_1\sqrt{1-\frac{1}{g_1 g_2}}+g_1-1 \\ \frac{1}{r_2} &= g_2\sqrt{1-\frac{1}{g_1 g_2}}+g_2-1 \end{aligned}}$$

- Single-pass magnification factor is the increase in radius of the spherical wave when propagating from one mirror to another:

$$\boxed{M_{12}=1+\frac{1}{r_1},\quad M_{21}=1+\frac{1}{r_2}}$$

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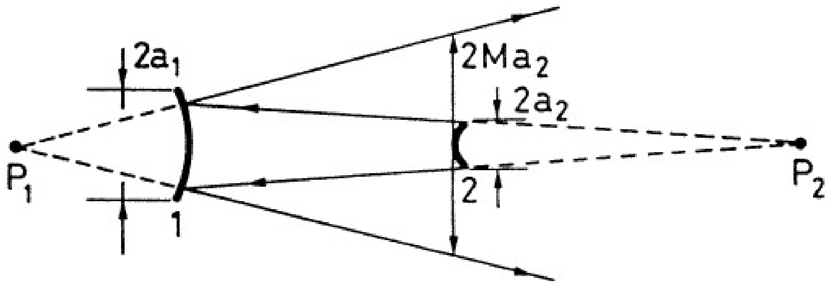
Geometrical-optics description

- Single-ended resonator (R_1=R_2=100%), round-trip magnification factor



$$M = M_{21} M_{12} = \left(1 + \frac{1}{r_1}\right)\left(1 + \frac{1}{r_2}\right)$$

$$= \left(2 g_1 g_2 - 1\right) - 2 g_1 g_2 \sqrt{1 - \frac{1}{g_1 g_2}}$$

- The round-trip loss (due to output) (Q: what is the loss coefficient?)

$$L_{out} = 1 - \frac{\pi a_2^2}{\pi \left(M a_2\right)^2} = 1 - \frac{1}{M^2}$$

Examples 5.10

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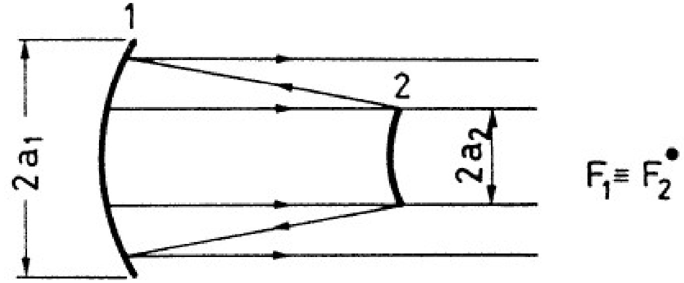
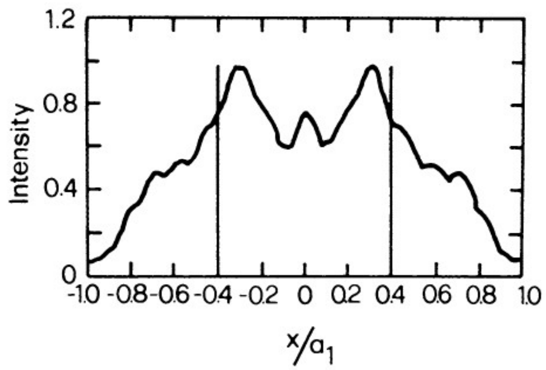
Wave-optics description

- The electric field distribution is obtained by the F-K intergral equation as well, using Fox-Li procedure.

- The first result is that the wave-optics description does indeed show that eigensolutions, that is, field profiels which are slef-producing after one-round trip, do exist also for unstable resonators.



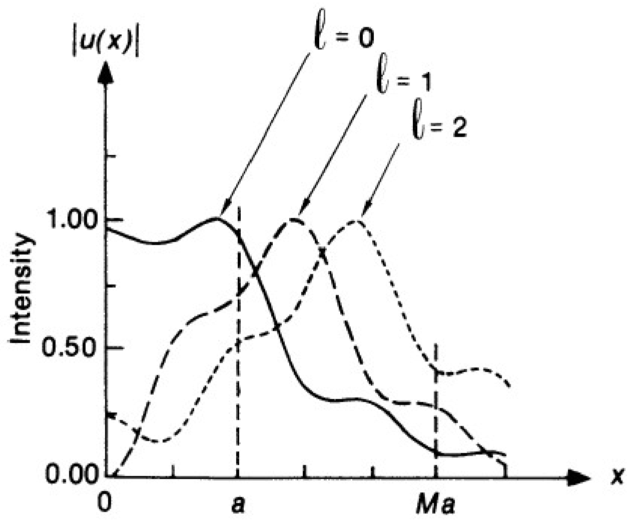


Beam profile at mirror 2, inside cavity

- Different to the uniform field amplitude in geometircal-optics theory, the intensity profile in wave-optics description have several diffraction rings arising from the sharp edges of mirror 2, due to the field diffraction.
- Wave-optics description shows spherical wavefront as geometrical-optics.

Wave-optics description

- The second result is that unstable resonators have different transverse modes, that is, different self-producing spatial patterns. These modes generally differ from each other in the location and strength of the diffraction rings.
- The mode labled l=0 shows a field amplitude distribution more concentrated toward the beam axis. Thus, this mode will have the lowest loss, and is the fundamental mode.



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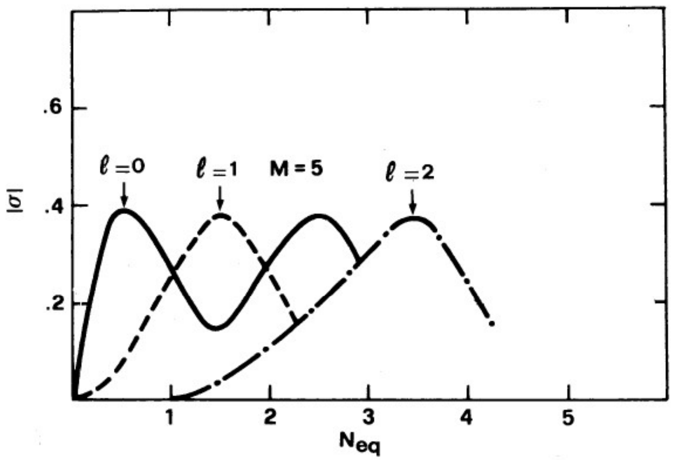
Wave-optics description

- The third result is that the lowest loss mode or the fundamental mode changes with the equivalent Fresnel number N_{eq}, that is, M, a2, or L.

$$N_{eq} = \frac{M-1}{2}\frac{a_2^2}{L\lambda} \text{ for postive branch}$$

$$N_{eq} = \frac{M+1}{2}\frac{a_2^2}{L\lambda} \text{ for negative branch}$$

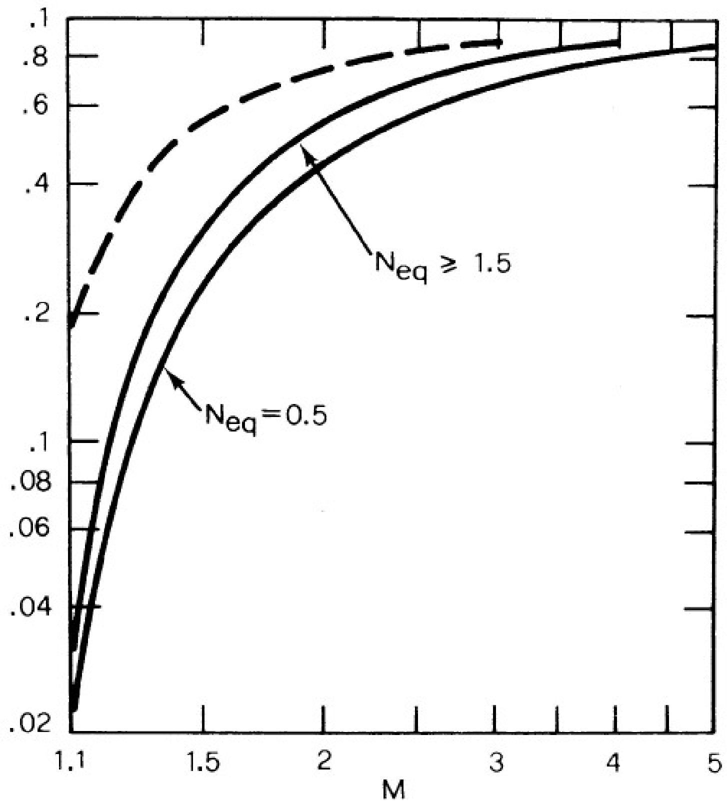


- At half-integer values of N_{eq}, there is a large difference between the lowest loss mode and other modes, that is, there is a large transverse-mode discrimination.

- At integer values of N_{eq}, two modes cross each other, so the intensity profiles of the two modes are identical. However, the two modes still differ with respect to the total round trip phase shift, that is, they differ in the longitudinal mode and thus their resonance frequencies.

Wave-optics description

- For the fundamental mode, the wave optics (solid lines) provides a smaller loss than the geometrical optics (dashed lines). Because the intensity is more concentrated toward the beam axis, rather than uniform across the mirror.



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Wave-optics description

- Advantages:
  - ✓ Large, controllable mode volume
  - ✓ Good transverse mode discrimination
  - ✓ All reflective optics (metallic mirror)
- Disadvantages:
  - ✓ The beam cross section is in the form of ring
  - ✓ The intensity distribution exhibits diffraction rings
  - ✓ The cavity is sensitive to perturbations.
- Prefered in high power lasers, with high gain and large active medium dimensions (large mode volume). On the other hand, the lasing threshold is high due to the high loss.

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Homework

5.1

5.2

5.4

5.6

5.7

5.8