第15卷 第12期 光 学 学 报 Vol. 15, No. 12
1995年12月 ACTA OPTICA SINICA December, 1995

Mixed Mode Coefficient and Gaussian-Like Distribution

J. Q. Yao * Y. Cui X. W. Sun * * M. H. Dunn W. Sibbett

(*J. F. Allen Physics Research Laboratories, Department of Physics and Astronomy University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland, UK*)

(Received 14 December 1994; revised 27 January 1995)

Abstract Starting from a sum of Hermite-Gaussian multimodes, the mixing mode coefficient is defined and the accurate expression of mixed mode coefficient M is derived. A Gaussian-like distribution (GLD) or Gaussian-like beam (GLB) is defined to describe and treat the mixed mode. The propagation and transformation of GLB in a homogeneous medium is discussed. Finally, a method for practical measurement of the coefficient, M, is given.

Key words mixed mode coefficient, Gaussian-like distribution, Gaussian-like beam.

1 Introduction

In many practial lasers, especially in high power lasers such as CO_2, excimer, Nd:YAG and high intensity diode laser pumped solid-state lasers, high order modes are concerned. The output of such lasers consists several high order modes in addition to the fundamental transverse mode. Important questions include how to describe the transverse distribution of this mixed mode beam, how to evaluate this distribution, and how to measure the parameters indicated by this mixed mode.

Describing and determining the spot size of a laser beam, whether in the near- or far-field is a fundamental problem of laser physics. The transverse profiles of real laser beams are sometimes very irregular in shape, displaying multiple peaks and lacking clearly defined edges. Even defining the width of a laser beam in a meaningful way can be difficult for an aberrated or multimode laser beam with an irregular intensity profile, let alone measuring this width experimentally.

In 1984 Yao and Xue defined a mixed mode coefficient M and GLB[1], while Siegman established the theory of M^2 by using spatial-frequency and intensity-moments analysis[4, 30~32]. Normalisation to

* J. Q. Yao is currently a visiting professor supported by the Royal Society, UK. His permanent address: Institute of Laser and Optoelectronics, Tianjing University, Tianjin 300072, China.

* * X. W. Sun is currently a student of Hong Kong University of Science and Technology.

the TEM_{00} mode gives a dimensionless number, the beam propagation factor M^2:

$$M^2 = (\langle x_0^2\rangle\langle\theta^2\rangle/\langle x_{00}^2\rangle\langle\theta_0^2\rangle)^{1/2} \geqslant 1$$

where $\langle x_0^2\rangle\langle\theta^2\rangle$ and $\langle x_{00}^2\rangle\langle\theta_0^2\rangle$ are the product of waist radius and far-field divergence of mixed mode and TEM_{00} mode.

A more practical approach and method of measurement for laser beam width, divergence and beam propagation factor was adopted by the international standardization organisation (ISO)[15, 28] and some other authors[5, 7, 13, 14, 16, 21, 23, 24, 26~29]. Another dimensionless parameter K, a beam quality number was introduced[11].

$$K = (\lambda/\pi w_{86.5}\theta_{86.5}) \leqslant 1$$

where $w_{86.5}$ and $\theta_{86.5}$ are the beam waist radius and beam far-field divergence in the 86.5% power content values.

Some authors have discussed characteristics of multimode beams[6, 8~12, 17~20, 22], but most of them just discussed some incoherent mixture of parameters for describing transversal distribution of a mixed mode beam. On the other hand, the second moment method fails if the transversal field is limited by steep edges. Several problems in describing and evaluating a mixed mode beam still remain.

In this paper, starting from a sum of Hermite-Gaussian multimodes, the mixed mode coefficient is defined and an accurate solution of the mixed mode coefficient is derived. A Gaussian-like distribution or Gaussian-like beam to decribe and treat the mixed mode is defined. The propagation and transformation of the GLB in a homogeneous medium and second harmonic generation with the beam passing through a nonlinear optical crystal is discussed. Finally, a method for practical measurement of the coefficient M is given.

2 Mixed Mode Coeffcient of Hermite-Gaussian Multimodes

According to resonator theory, the amplitude of a particular high-order mode for a square symmetry beam (in rectangular coordinates) is a Hermite-Gaussian function given by[2]

$$U_{mn}(x, y, z) = \frac{Aw(0)}{w(z)} H_m(\frac{\sqrt{2}}{w_x(z)}) H_n(\frac{\sqrt{2}y}{w_y(z)}) \exp\left[-\frac{x^2}{w_x^2(z)} - \frac{y^2}{w_y^2(z)}\right] \times \exp\left\{-i\left[k\frac{x^2+y^2}{2R(z)} + kz - (m+n+1)\,\mathrm{tg}^{-1}(\frac{z}{z_0})\right]\right\} \quad (1)$$

where $w_x(z)$ and $w_y(z)$ are spot radii of a fundamental mode Gaussian beam along the x and y axes respectively. The more general case with $w_x(z) \neq w_y(z)$ is assumed. $R(z)$ is the radius of the wavefront. $w_x(z)$, $w_y(z)$ and $R(z)$ are independent of m, n, and all high-oder beam are characterised by some values of $R(z)$ and $w(z)$ as the fundamental mode. Each mode of order (m, n) remains a Gaussian beam of same order after propagation in free space or transformation by a thin lens or a spherical mirror, but its q parameter is changed according to the ABCD law.

The field of mixed mode is a sum of the field of all modes

$$E(x, y, z) = \sum_{m=0}^{M}\sum_{n=0}^{N} C_{mn} U_{mn}(x, y, z) \exp(iv_{mn}t) \quad (2)$$

where C_{mn} is the complex amplitude coefficient of different modes included. Furthermore, U_{mn} can be written as follows

$$U_{mn}(x, y, z) = A_{mn} H_m(\frac{\sqrt{2}x}{w_x(z)}) H_n(\frac{\sqrt{2}y}{w_y(z)}) \exp\left[-\frac{x^2}{w_x^2(z)} - \frac{y^2}{w_y^2(z)}\right] \exp(-i\phi_{mn}) \quad (3)$$

where ϕ_{mn} is the total phase shift of the Hermite-Gaussian mode. ϕ_{mn} indicates the energy rate of a particular mode in the mixed mode. It is assumed that ϕ_{mn} is a function of variable z only. $U_{mn}(x, y, z)$

and C_{mn} must satisfy

$$\iint_{-\infty}^{+\infty} |U_{mn}(x, y, z)|^2 dxdy = 1, \qquad \sum_{m=0}^{M}\sum_{n=0}^{N} |C_{mn}|^2 = 1 \tag{4}$$

From (4) the normalised coefficient of $U_{mn}(x, y, z)$

$$A_{mn}^2 = \frac{1}{2^{m+n-1}\, m!\, n!\, \pi\, w_x(z)\, w_y(z)} \tag{5}$$

Taking $m = n = 0$, the amplitude of the fundamental Gaussian-mode can be written

$$U_{00}(x, y, z) = A_{00} \exp\left[-\frac{x^2}{w_x^2(z)} - \frac{y^2}{w_y^2(z)}\right] \exp(-i\phi_0) \tag{6}$$

Similar to the definition of spot radius of the fundamental Gaussian-mode, the spot radius of the mixed mode is defined as:

$$w_{M,x}^2(z) = 4\iint_{-\infty}^{+\infty} x^2 |E(x, y, z)|^2 dxdy, \qquad w_{M,y}^2(z) = 4\iint_{-\infty}^{+\infty} y^2 |E(x, y, z)|^2 dxdy \tag{7}$$

Substituting Eq(2) into Eq(7) and assuming $X = \sqrt{2}\, x/w_x(z)$, $Y = \sqrt{2}\, y/w_y(z)$ we have

$$\begin{aligned} w_{M,x}^2(z) &= 4\iint_{-\infty}^{+\infty} x^2 \left| \sum_{m=0}^{M}\sum_{n=0}^{N} C_{mn} A_{mn} H_m(X) H_n(Y) \exp\left(-\frac{X^2}{2} - \frac{Y^2}{2}\right) \exp(-i\phi_{mn}) \right|^2 dxdy \\ &= 4\iint_{-\infty}^{+\infty} \sum_{m=0}^{M}\sum_{n=0}^{N} |C_{mn}|^2 A_{mn}^2 x^2 H_m^2(X) H_n^2(Y) \exp(-X^2 - Y^2)\, dxdy \\ &\quad + 2\iint_{-\infty}^{+\infty} \sum_{m=1}^{M-2}\sum_{n=0}^{N} |C_{mn} C_{(m+2)n}|\, A_{mn} A_{(m+2)n} 2x^2 H_m(X) H_{m+2}(X) H_n^2(Y) \\ &\quad \cdot \exp(-X^2 - Y^2) \left[\cos(\phi_{mn} + \phi_{(m+2)n}) + \cos(\phi_{mn} - \phi_{(m+2)n})\right] dxdy \\ &\quad + 2\iint_{-\infty}^{+\infty} \sum_{m=1}^{M}\sum_{n=0}^{N} |C_{0n} C_{2n}|\, A_{0n} A_{2n} 2x^2 H_m(x) H_n(Y) \exp(-X^2 - Y^2) \\ &\quad \cdot \left[\cos(\phi_{0n} + \phi_{2n}) + \cos(\phi_{0n} - \phi_{2n})\right] dxdy \end{aligned} \tag{8}$$

$$w_{M,x}^2(z) = A + B + C \tag{9}$$

where A indicates the distribution of all modes included in the mixed mode to the spot radius of mixed mode, and B and C indicate the distribution of interaction between all the modes included in the mixed mode to the spot radius of the mixed mode. In other words reaction "is coherent". From Eq(8), if $m < 2$, then $B = 0$ and $C = 0$, $w_{M,x}^2(z) = A$. Integrating equation (8) we find

$$\begin{aligned} w_{M,x}^2(z) = w_x^2(z) \Big\{ &\sum_{m=0}^{M}\sum_{n=0}^{N} (2m+1) |C_{mn}|^2 + \sum_{m=0}^{M-2}\sum_{n=0}^{N} \sqrt{(m+1)(m+2)}\, |C_{mn} C_{(m+2)n}| \\ &\cdot \left[\cos(\phi_{mn} + \phi_{(m+2)n}) + \cos(\phi_{mn} - \phi_{(m+2)n})\right] \Big\} \end{aligned} \tag{10}$$

By the same method we obtain

$$\begin{aligned} w_{M,y}^2(z) = w_y^2(z) \Big\{ &\sum_{m=0}^{M}\sum_{n=0}^{N} (2n+1) |C_{mn}|^2 + \sum_{m=0}^{M}\sum_{n=0}^{N-2} \sqrt{(n+1)(n+2)}\, |C_{mn} C_{m(n+2)}| \\ &\cdot \left[\cos(\phi_{mn} + \phi_{m(n+2)}) + \cos(\phi_{mn} - \phi_{m(n-2)})\right] \Big\} \end{aligned} \tag{11}$$

From Eq(10) and Eq(11) one can define the mixed mode coefficient along the x and y axes in rectangular coordinates:

$$\begin{aligned} M_x^2 = &\sum_{m=0}^{M}\sum_{n=0}^{N} (2m+1) |C_{mn}|^2 + \sum_{m=0}^{M-2}\sum_{n=0}^{N} \sqrt{(m+1)(m+2)}\, |C_{mn} C_{(m+2)n}| \\ &\cdot \left[\cos(\phi_{mn} + \phi_{(m+2)n}) + \cos(\phi_{mn} - \phi_{(m+2)n})\right] \end{aligned} \tag{12}$$

$$M_y^2 = \sum_{m=0}^{M}\sum_{n=0}^{N} (2n+1) |C_{mn}|^2 + \sum_{m=0}^{M}\sum_{n=0}^{N-2} \sqrt{(n+1)(n+2)}\, |C_{mn} C_{m(n+2)}|]$$

$$\cdot \left[\cos (\phi_{mn} + \phi_{m(n+2)}) + \cos (\phi_{mn} - \phi_{m(n+2)}) \right] \quad (13)$$

The mixed mode coefficients M_x^2 and M_y^2 defined by Eqs(12) and (13) has been assumed that the modes making up the mixed mode are total incoherent. In general there is partial coherence between these modes especially in real laser systems. To account for partial coherence, a coherence coefficient, $k_{mn,(m+2)n}$ was introduced which is coherence between U_{mn} mode and $U_{(m+2)n}$ mode. Eqs(12) and (13) become

$$M_x^2 = \sum_{m=0}^{M} \sum_{n=0}^{N} (2m+1) \ |C_{mn}|^2 + \sum_{m=0}^{M-2} \sum_{n=0}^{N} k_{mn,(m+2)n} \sqrt{(m+1)(m+2)} \ |C_{mn}C_{(m+2)n}|$$
$$\cdot \left[\cos (\phi_{mn} + \phi_{(m+2)n}) + \cos (\phi_{mn} - \phi_{(m+2)n}) \right] \quad (14)$$

$$M_y^2 = \sum_{m=0}^{M} \sum_{n=0}^{N} (2n+1) \ |C_{mn}|^2 + \sum_{m=0}^{M} \sum_{n=0}^{N-2} k_{mn,m(n+2)} \sqrt{(n+1)(n+2)} \ |C_{mn}C_{m(n+2)}|$$
$$\cdot \left[\cos (\phi_{mn} + \phi_{m(n+2)}) + \cos (\phi_{mn} - \phi_{m(n+2)}) \right] \quad (15)$$

From Eq(12) and Eq(13) we have

$$w_{M,x}^2(z) = M_x^2 w_x^2(z), \qquad w_{M,y}^2(z) = M_y^2 w_y^2(z) \quad (16)$$

For the circularly symmetric case (in polar corrdinates), the formula, becomes

$$w_{M,r}^2(z) = M_r^2 w_r^2(z) \quad (17)$$

In summary, for the two situations we can write simply as follows

$$w_M^2(z) = M^2 w^2(z) \quad (18)$$

where $w_M(z)$ and $w(z)$ are beam spot radii of the mixed mode and fundamental mode, respectively, at any position z. For the beam waist ($z = 0$) it is true that

$$w_M^2(0) = M^2 w^2(0) \quad (19)$$

Equations (12) and (19) define a mixed mode coefficient, M, which has the same meaning as that of Siegman[5], although drived through a different method. The mixed mode coefficient M (or M^2) is a function of m, n and with C_{mn}, only independent of z. If a laser has a stable transverse mode structure, the values of M (or M^2) and $w_M(z)$ are also stable.

3 Definition and Features of GLB

By comparison with a fundamental Gaussian beam (FGB) we can define the spot radius, radius of wavefront, near and far field divergence of the mixed mode can be defined as

$$w_M(z) = w_M(0) \sqrt{1 + \left(\frac{\lambda z}{\pi w_M^2(0)} \right)^2 M^4}, \qquad R_M(z) = z \left[1 + \left(\frac{\pi \, w_m^2(0)}{\lambda z} \right)^2 \frac{1}{M^4} \right] \quad (20)$$

$$\theta_M(z) = \frac{dw_M(z)}{dz} = M^4 \frac{\lambda^2 z}{\pi^2 w_M^2(0)} \left[1 + \left(\frac{\lambda z}{\pi w_M^2(0)} \right)^2 M^4 \right]^{-1/2}, \qquad \theta_M(z \to \infty) = \frac{\lambda M^2}{\pi w_M(0)} \quad (21)$$

With these definition, the mixed mode distribution can be identified as a Gaussian-like distribution or Gaussian-like beam. The spot radius of GLB is amplified M times over that of the FGB. When $M = 1$ equations (20), (21) are the same as for a fundamental Gaussian beam, and the GLB becomes a FGB. In this sense, the FGB is just a special case of a Gaussian-like beam with $M = 1$, while the GLB is a universal distribution. If M is greater than one the behaviour of GLB deviates from that of the FGB. In order to observe the effect of M, let the GLB and FGB (with same spot radii) propagate in some homogeneous medium. The ratio of the spot radii for two beam is

$$\zeta = \frac{w_M(Z)}{w(z)} = \sqrt{\frac{1 + (\lambda z / \pi w_M^2(0))^2 M^4}{1 + (\lambda z / \pi w_M^2(0))^2}} \quad (22)$$

When z is great, $\zeta = M^2$, i. e. the spot radius of GLB is proportion to M^2 as the distance from the waist becomes large enough. The behaviour of the FGB can only be characterised by one parameter, the spot radius at waist $w(0)$. However, two parameters, i.e. the spot radius at waist $w_M(0)$ and mixed mode coefficient M (or M^2) must be used to characterise GLB.

4 Propagation and Transformation of GLB in a Homogeneous Medium

When a GLB with a spot radius $w_M(0)$ and mixed mode coefficient M (or M^2) passes through a thin lens with a focal length of f_1 (see figure 1), the following relations exist between the two waist spot radii ($w_{M_1}(0)$ and $w_{M_2}(0)$) and the two distance (d_1 and d_2)

$$d_2 = \frac{f_1(\pi w_{M_1}^2(0)/\lambda M^2)^2 + f_1 d_1^2 - d_1 f_1^2}{f_1^2 - 2f_1 d_1 + d_1^2 + (\pi w_{M_1}^2(0)/\lambda M^2)^2} \tag{23}$$

$$w_{M_2}(0) = w_{M_1}(0)\left[1 - \left(\frac{d_1}{f_1}\right)^2 + \left(\frac{\pi w_{M_1}^2(0)}{\lambda f_1 M^2}\right)^2\right]^{-1/2} \tag{24}$$

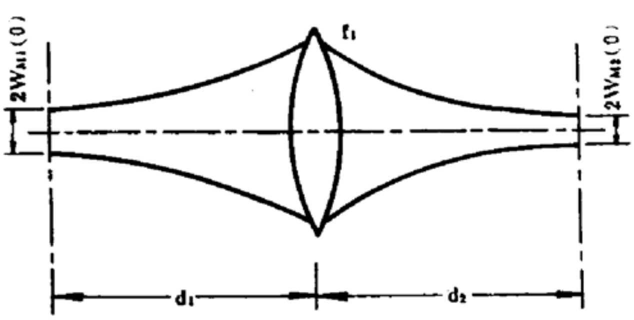

Fig. 1 Lens transformation of GLB. f_1: focal length of lens, $w_{M_1}(0)$ and $w_{M_2}(0)$ are spot rarii of GLB at waist, d_1 and d_2 are distances between the lens and the two waists

a) Focus case, i.e. $d_1 \gg f_1$, from (23) and (24) we have

$$w_{M_2}(0) = w_{M_1}(0)\ f_1\left[d_1^2 + (\pi w_{M_1}^2(0)/\lambda M^2)^2\right]^{-1/2} \tag{25}$$

If $\pi w_{M_1}^2(0)/(\lambda M^2) \ll d_1$, then $w_{M_2}(0) = w_{M_1}(0)\ f_1/d_1$, because $d_1 \gg f_1$, so $w_{M_2}(0) \ll w_{M_1}(0)$. If $d_1 = 0$ and $\pi w_{M_1}^2(0)/(\lambda M^2) \gg f_1^2$, then $d_2 \approx f_1$, and $w_{M_2}(0) \approx \lambda M^2 f_1/[\pi w_{M_1}^2(0)]$. Thus $w_{M_2}(0)$ is proportional to M^2 and f_1, is inversely proportional to $w_{M_1}^2(0)$. Choosing the lens with shorter focal length and extending the incident beam are beneficial for focusing purpose. The focus of the beam with the greater M value is different.

b) Alignment case

$$\theta_{M_2}(z) = \lim_{z\to\infty}[w_{M_2}(0)/z] = [\lambda M/\pi w_{M_1}(0)]\sqrt{(1-d_1/f_1)^2 + [\pi w_{M_1}^2(0)/\lambda f_1 M^2]^2} \tag{26}$$

$$\theta_{M_2}(z)/\theta_{M_1}(z) = \sqrt{(1-d_1/f_1)^2 + [\pi w_{M_1}^2(0)/\lambda f_1 M^2]^2} \tag{27}$$

Choosing the parameters so that $d_1 = f_1$, and $\pi w_{M_1}^2(0)/(\lambda f_1 M^2) \ll 1$, then $\theta_{M_2} \ll \theta_{M_1}$, i.e. a smaller divergence is obtained for alignment purposes.

c) Self-consistant case from Eqs(23) and (24), let $d_1 = d_2$, and $w_{M_1}(0) = w_{M_2}(0)$, then the condition for self-consistant can be derived using the following expression

$$f_1 = \{d_1^2 + [\pi^2 w_M^4(0)/\lambda^2 M^4]\}/(2d_1) \tag{28}$$

If this condition can be satisfied, the beams on both sides of the lens are identical, the condition can be used to design a resonator with a GLB.

5 Practical Measurement of GLB

For a practical laser beam it is very hard to know the modes included and the amplitudes of individual modes. According to the above analysis, a method to determine the M and $w_M(0)$ can be derived, and thereby the transverse distribution of the laser output calculated. Here two different cases of a circularly symmetric beam will be discussed: (1) the output coupling mirror is the plane at which the waist is located, (2) the output coupling mirror is a curved mirror whose radius is known.

In the first case (see figure 2) the measured laser powers at two position, z_1 and z_2 (measured from the output coupler) along the output optical axis, through a pinhole and without a pinhole, respectively, are $P_{r_0}(z_1)$, $P_\infty(z_1)$, $P_{r_0}(z_2)$ and $P_\infty(z_2)$. Here r_0 is the radius of the pinhole. $P_\infty(z_1)$ is

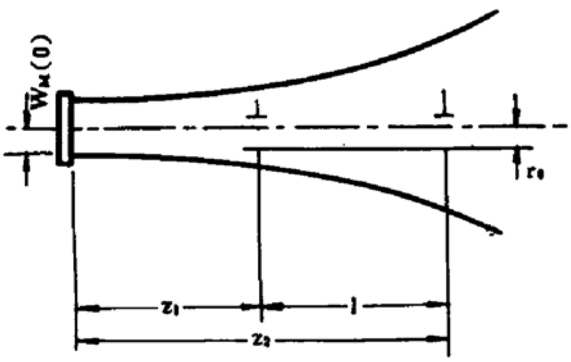

Fig. 2 Diagram for measuring M and $w_M(0)$, r_0, z_1, z_2 are radius and positions of pinhole

same with $P_\infty(z_2)$. Let $P_\infty(z_1) = P_\infty(z_2) = P_\infty$. For beam propagation in free space, the energy of the GLB should be constant, so

$$(\pi/2)\, w_M^2(0)\, (E_0)^2 = (\pi/2)\, w_M^2(z)\, E^2(z)$$

$$w_M^2(z) = 2r_0^2 \frac{1}{\ln\{P_\infty/[P_\infty - P_{r0}(z)]\}} = \frac{2r_0^2}{A} \tag{29}$$

The spot radii at of two positions (z_1, and z_2) are

$$w_M(z_1) = \sqrt{2}\, r_0/\sqrt{A_1},$$
$$w_M(z_2) = \sqrt{2}\, r_0/\sqrt{A_2}$$
$$A_1 = \ln\{P_\infty/[P_\infty - P_{r0}(z_1)]\},$$
$$A_2 = \ln\{P_\infty/[P_\infty - P_{r0}(z_2)]\} \tag{30}$$

For far field divergence

$$\theta = [w_M(z_2) - w_M(z_1)]/(z_2 - z_1) = \lambda M^2/\pi w_M(0) \tag{31}$$

so

$$w_M(0) = M^2 U \tag{32}$$

$$U = \frac{\lambda l}{\sqrt{2}\, r_0 \pi (1/\sqrt{A_2} - 1/\sqrt{A_1})}, \qquad l = z_2 - z_1 \tag{33}$$

Hence

$$M^2 = \frac{\lambda}{\pi U^2} \sqrt{\frac{A_2 z_2^2 - A_1 z_1^2}{A_2 - A_1}}, \qquad (z_2 > z_1) \tag{34}$$

M and $w_M^2(0)$ are thus obtained from Eq(34) and Eq(32).

For the second case, assuming the waist point is know (see figure 3), z_1 and z_2 are the distance from the waist. By the same treatment as above, one can calculate M and $w_M(0)$ by measuring parameters.

If the position of the waist is not known, but the radius of curvature of the output mirror, R_M is known, then using equation Eq(20)

$$R_M = z_M [1 + (\pi w_M^2(0)/\lambda\, z_M)^2 (1/M^4)] \tag{35}$$

By Eq(45~Eq(47) and $l = z_2 - z_1$, then

$$R_M = z_M [1 + \pi^2 M^4 U^4/\lambda^2 z_M^2] \tag{36}$$

Substuting z_M for z_1 and $z_M + l$ for z_2 in Eq(46) obtains:

$$M^2 = (\lambda/\pi U^2)\ \sqrt{[A_2^2(z_M + l)^2 - A_1 z_M^2]/(A_1 - A_2)} \tag{37}$$

$$z_M = A_2 l^2/[R_M(A_1 - A_2) - 2lA_2] \tag{38}$$

From z_M and U, then one can obtain M and $w_M(0)$.

Using the method above experimentlly determined values of M versus pumping current I, are plotted in figure 4 for an intracavity-doubled Nd:YAG laser with a different pinhole size (d) inside the cavity, two pumping K_r lamps (the solid line corresponds to low pressure lamps, the dashed line corresponds to a high pressure lamp). The data shown in the figure demonstrate that the smaller the dimeter of the inhole, the closer the M value is to one (i. e. TEM_{00} mode case). The larger the pumping cureent, the more the M value deviates from one. The high pumping conversion efficiency with the high pressure lamps results in correspondingly higher output power and larger M value.

According to this method an instrument can be designed to measure M and $w_M(0)$ of GLB to determine the characteristics of the mixed mode. From this data, the laser resonantor design can be determined to obtain optimal laser output power and beam quality.

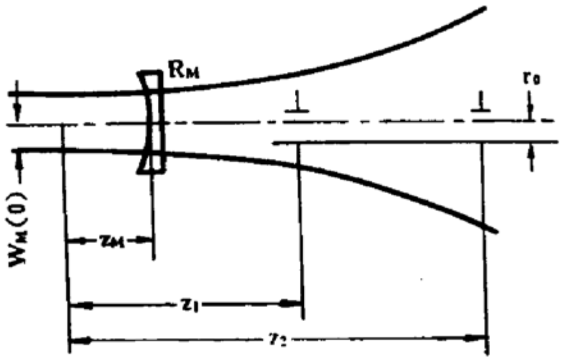

Fig. 3 Diagram for measuring M and $w_M(0)$ (for the case where the waist is not located on the output coupled mirror), where z_M is the distance between waist and output mirror

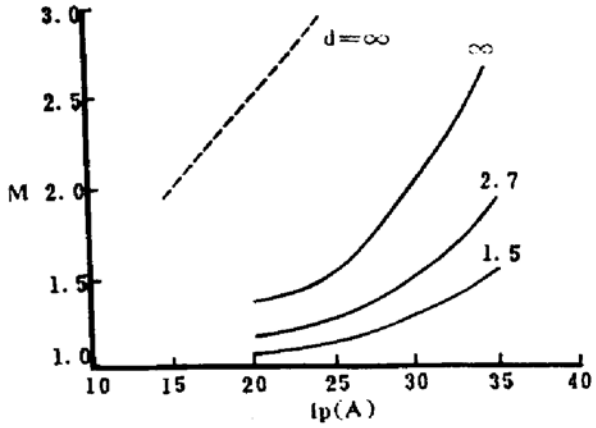

Fig. 4 Experimental mesurements of M

References

[1] J. Q. Yao, B. Xue, Gaussian-like distribution theory and its applications. *Quant. Electron.* 1984, 1(2): 133~142

[2] A. E. Siegman, Laser, 1, Mill Valley (CA), *University Science Books*, 1986

[3] R. L. Byer, *Parametric oscillators and nonlinear meterials*, *in Nonlinear Optics*, Edited by P. G. Harper and B. S. Wherrett, Academic Press, 1977, 47~160

[4] G. Names, A. E. Siegman, Measurement of all ten second-order moments of an astigmatic beam by the use of rotating simple astigmatic (anamorphic) optics. *J. Opt. Soc. Am. A*, 1994, **11**(8): 2257~2264

[5] A. E. Siegman, M. W. Sasnett, T. F. Johnston, Choice of clip levels for beam width measurements using knife-edge techniques. *IEEE J. Quant. Electron.*, 1991, **QE-27**(4): 1098~1104

[6] A. E. Siegman, Defining the effective radius of curvature for a nonideal optical beam. *IEEE J. Quant. Electron.*, 1991, **QE-27**(5): 1146~1148

[7] J. A. Ruff, A. E. Siegman, Single-pulse laser beam quality measurements using a CCD camera system. *Appl. Opt.*, 1992, **31**(24): 4907~4909

[8] H. Weber, *Journal of Modern Optics*, 1992, **39**: 543

[9] N. Hodgson, H. Weber, *Journal of Modern Optics*, 1992, **39**: 1873

[10] H. Weber, *Optical and Quant. Electron.*, 1992, **24**: 7

[11] H. Weber, Some historial and technical aspects of beam quality. *Opt. and Quant. Electron.*, 1992, **24**: S861~S864

[12] N. Hodgson, T. Haase, R. Kostka *et al.*, *Opt. and Quant. Electron.*, 1992, **24**: S961~971

[13] A. Cutolo, F. Ferreri, T. Isernia *et al.*, Measurments of the waist and the power distribution across the transverse modes of a laser beam. *Opt. and Quant. Electron.*, 1992, **24**: S961~971

[14] N. Reng, B. Eppich, Definition and measurements of high-power laser beam parameters. *Opt. and Quant. Electron.*, 1992, **24**: S961~971

[15] D. Wright, P. Greve, J. Fleischer *et al.*, Laser beam width, divergence and beam propagation factor-an international standardization approach. *Opt. and Quant. Electron.*, 1992, **24**: S993~S1000

[16] A. Caprara, G. C. Reali, Time varying M^2 in Q-switched lasers. *Opt. and Quant. Electron.*, 1992, **24**: S1001~S1009

[17] H. Weber, Propagation of higher-order intensity moments in quadratic-index media. *Opt. and Quantum Electron.*, 1992, **24**: S1027~S1049

[18] C. Pare, P. A. Belanger, Beam propagation in a linear or nonlinear lens-like medium using ABCD ray matrices: the method of moments. *Opt. and Quant. Electron.*, 1992, **24**: S1051~S1070

[19] A. Parent, M. Morin, P. Lavigne, Propagation of super-Gaussian field distribution. *Opt. and Quant. Electron.*, 1992, **24**: S1071~S1079

[20] K. M. Du, G. Herziger, P. Loosen *et al.*, Coherence and intensity moments of laser light. *Opt. and Quant.*

Electron., 1992, **24**: S1081～S1093

[21] K. M. Du, G. Herziger, P. Lossen *et al.*, Measurement of the mode coherence coefficients. *Opt. and Quant. Electron.*, 1992, **24**: S1119～S1127

[22] A. E. Siegman, S. W. Townsend, Output beam propagation and beam quality from a multimode stable-cavity laser. *IEEE J. Quant. Electron.*, 1993, **QE-29**(4): 1212

[23] R. D. Jones, T. R. Scott, Error propagation in laser beam spatial parameters. *Opt. and Quant. Electron.*, 1994, **26**: 25～34

[24] G. N. Lawrence, Proposed international standard for laser-beam quality falls shat. *Laser Focus World*, 1994, **30**: 109～114

[25] J. Q. Yao, B. Xue, High conversion intracavity frequancy doubled laser with Gauss and Gauss-like beam. *Acta Optica Sinica*, 1985, **5**(2): 142～150

[26] R. D. Jones, T. R. Scott, Laser-beam analysis pinpoints critical parameters. *Laser Focus World*, 1993, **29**(1): 123～130

[27] A. C. Ashmead, Watch out for diffraction effects on laser-beam profiles. *Laser Focus World*, 1991, **27**(8): 83～92

[28] T. F. Johnston, M. W. Sasnett, Laser quality versus aperture size in a cw argon-ion laser. *Opt. Lett.*, 1992, **17**(3): 198～200

[29] A. E. Siegman, Analysis of laser beam quality degradation caused by quartic phase aberrations. *Appl. Opt.*, 1993, **32**(30): 5893～5901

[30] A. E. Siegman, Binarry phase plates cannot improve laser beam quality. *Opt. Lett.*, 1993, **18**(9): 675～677

[31] A. E. Siegman, Defining and measuring laser beam parameters, Workshop on laser Beam Characterization, Universidad Complutense de Madrid, Madrid, Spain, 1993, 14～16 June

[32] A. E. Sieman, Defining, measuring, and optimizing laser beam quality, Published in Laser Resonators and Coherent Optics: Modeling, Technology, and Applications, *Proceeding SPIE*, 1993, **1868**

[33] G. Nemes, Synthesis of general astigmatic optical systems, the detwisting procedure, and the beam quality factors for general astigmatic laser beams, *2-nd International Workshop on Laser Beam Characterization*, Berlin, Germany, 1994, 30 May-1 June

混合模系数与类高斯分布

姚建铨 Y. Cui 孙小卫 M. H. Dunn W. Sibbett

(Department of Physics and Astronomy, U. of St. Andrews, Fife, KY16 9SS, Scotland, UK)

(收稿日期:1994年12月14日;收到修改稿日期:1995年1月27日)

摘 要 从 Hermite-Gaussian 模的求和出发定义了混合模系数,并推导了混合模系数 M 的精确表达式。进而定义了描述及处理混合模的类高斯分布(GLD)及类高斯光束(GLB)。讨论了类高斯光束在均匀介质中的传播。最后给出了一种实际测量系数 M 的方法。

关键词 混合模系数, 类高斯分布, 类高斯光束。