Progress in New Laser Beam on Optical Beam Quality

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The historical and present research work of our group in laser beam on optical beam quality is reviewed in this paper. An invented intracavity CO₂ laser with $M_e^2 < 1$ is presented, and the optical beam quality of beam from subwavelength aperture is investigated. Equivalent optical beam quality of quantum well laser beam is demonstrated. The progress will promote scientific development in correlative fields, also bring potential applications for optical industry.

Key Words: Optical beam quality, Equivalent optical beam quality, Intracavity CO₂ laser, Subwavelength aperture, Quantum well laser

1. Introduction

Since the advent of laser, the researches on the laser beam quality and laser beam propagation rule have been an active field of laser subject, which have pushed the development of laser science and technology. In 1990, M^2 factor theory put forward by A. E. Siegman brought the researches on this field into a new stage and offered a unified standard for evaluating properly paraxial beam quality.¹⁾ Therefore, M^2 factor is called optical beam quality factor. As the ISO standard,²⁾ M^2 factor must be greater than or equal to unity, and the transverse fundamental mode Gaussian beam is regarded as a diffraction limited beam and has the best optical beam quality. M^2 factor is calculated by using the second order method. In some cases, however, the integral of the second order method is infinite. To overcome this difficulty, the equivalent optical beam quality factor M_e^2 is suggested by ISO. M_e^2 is calculated by using the power content method, which regulates that the power in region of the beam waist and far field divergence angle is 86.5 % of the total power.³⁾ M_e^2 is much close to the practice.

In the past decades, however, a series of laser beam with $M_e^2 < 1$ have realized experimentally.^{4,5)} Meanwhile, nonparaxial vectorial moment theory of light beam propagation and propagation law of the power density second moment for diffracted scalar light beam have been developed.^{6,7)} M^2 factor is extended to the case of nonparaxial beam and can be theoretically smaller than unity.

This paper is organized as follows. In Section 2, an intracavity CO₂ laser beam with $M_e^2 < 1$ is reviewed. The optical beam quality of beam from subwavelength aperture is presented in Section 3. In Section 4, the equivalent optical beam quality of quantum well laser is demonstrated. Finally, we summarize our research work in Section 5.

2. An intracavity CO₂ laser beam with $M_e^2 < 1$

According to boundary diffraction wave theory, the light in-

tensity distribution of diffracted wave in the far field is coherent superposition of the geometrical beam and boundary diffraction beam. Moreover, the boundary beam possesses a phase jump of π compared with the incident wave.⁸⁾ If a phase π is added to the geometrical beam, the geometrical beam will have the same phase as the boundary beam. The interference of these two beams will form a new beam with higher central intensity and higher directivity than the incident beam. According to above analysis, new beams are successfully produced by He-Ne laser,⁹⁾ CO₂ laser¹⁰⁾ and solid state slab laser.¹¹⁾ However, it should be stated that fundamental mode beam source is required to generate these kinds of new beams, and there exists loss of energy and side lobes, which restricts the extended applications. To eliminate the side lobes, a $\lambda/2$ phase plate is inserted inside the rear mirror of a half confocal cavity of CO₂ laser (wavelength $\lambda = 10.6 \mu\text{m}$), which is shown in Fig. 1. Then the multi-mode oscillation and side lobes are restrained. In our experiment, the parameters of the resonator is chosen as $R_1 = \infty$, $R_2 = 1000 \text{ mm}$, the cavity length $L = 500 \text{ mm}$, and the diameter of phase plate small enough compared with a beam diameter on the rear mirror.

The output beam is superior to the fundamental mode Gaussian beam.¹²⁾ The output power is 17 W. For this type of CO₂ laser without phase plate, the maximum multi-mode output power is 19 W, and the maximum fundamental-mode output power is 8 W.

Based on the ISO standard, the new beam from this type of CO₂ laser is measured by Chinese National Institute of Metrology. The measurement setup is shown in Fig. 2. The beam width is measured by means of the second moment order method and the variable aperture method. The measured beam width after transformation of lens with $f = 1.0 \text{ m}$ is given in Fig. 3. For comparison, the propagation curve of fundamental mode Gaussian beam with the same beam waist is depicted in Fig. 3. According to hyperbolic fit to the measured beam width, the optical beam quality factor and the equivalent optical beam quality factor are 0.62 and 0.59, respectively.

The mode of the half confocal laser shown in Fig. 1 can be

Fig. 1 The configuration of CO₂ half confocal laser with $\lambda/2$ phase plate.

Fig. 2 The measurement setup based on ISO standard.

Fig. 3 The measured beam width after transformation of lens with $f=1.0$ m. The propagation curve of fundamental mode Gaussian beam with the same beam waist is depicted for comparison.

regarded as axial superposition of the boundary diffraction point source wave and two quasi-geometrical waves.¹³⁾ The propagation law of the second order moment beam width is

$$W^2(z) = \frac{a^2 \left\{ (z^2 + L^2) \left[4(z^2 + L^2)^2 + k^2(z^2 - L^2)^2 a^4 L^2 \right] + 4[z^2 - L^2] \left[4(z^2 + L^2)^2 + k^2(z^2 - L^2)^2 a^4 L^2 \right] \right\}}{\left[4(z^2 + L^2)^2 + k^2(z^2 - L^2)^2 a^4 L^2 \right] + 4[z^2 - L^2] \left[4(z^2 + L^2)^2 + k^2(z^2 - L^2)^2 a^4 L^2 \right]}, \quad (1)$$

where $k = 2\pi/\lambda$ is wavenumber, and $a = 0.0023$ is diffraction controlled parameter.

The beam waist located at the output mirror is given by

$$W_0 = W(0) = aL \sqrt{\frac{(4 + k^2 a^4 L^2)^2 + 4(4 - k^2 a^4 L^2)}{(4 + k^2 a^4 L^2)(8 + k^2 a^4 L^2)}}. \quad (2)$$

The far field divergence angle is defined as

$$\theta_\infty = \lim_{z \rightarrow \infty} \frac{W(z)}{z} = \frac{W_0}{L}. \quad (3)$$

After mathematic calculation, the optical beam quality factor M^2 is 0.56 and is well accordant with the experimental result.

The new beam CO₂ lasers have been awarded by the National Technical Invention of China in 1997. Now, this type laser is applied to laser radar and fine laser marker. Some new beam CO₂ lasers produced by collaborator are on sale abroad to Europe, Korea and USA.

3. Optical beam quality of beam from subwavelength aperture

A plane wave described by

$$U_i(r, z) = \exp(ikz) \quad (4)$$

is normally incident on a co-axial small circular aperture with radius R . A suitable Cartesian coordinate system is shown in Fig. 4. The small circular aperture plane is chosen as the $x-y$ plane, and the center of the small circular aperture is set at the origin. The z -axis is taken to be the beam propagating direction. The radius R of the small circular aperture is the order of the wavelength λ .

By solving the Helmholtz equation combined with the Kirchhoff's boundary condition, the diffracted field in the half space $z \geq 0$ is

$$U(r, z) = kR \int_0^\infty J_1(k\alpha R) \exp(ik\gamma z) J_0(k\alpha r) d\alpha, \quad (5)$$

where J_0 and J_1 are zero and first order Bessel functions of the first kind, respectively. $r^2 = x^2 + y^2$, and $\gamma = \sqrt{1 - \alpha^2}$. Values of $\alpha < 1$ correspond to homogeneous plane waves propagating at angles $\arcsin \alpha$ with respect to the z axis, whereas values of $\alpha > 1$ correspond to evanescent plane waves.

The accurate expression of light intensity for wide angle beam is¹⁴⁾

$$I = \text{Re} \left(\frac{U^*(r, z)}{ik} \frac{\partial U(r, z)}{\partial z} \right), \quad (6)$$

where Re denotes taking the real part, and the asterisk stands for the complex conjugate. At any beam cross-section, the total power of the diffracted beam is

$$\begin{aligned} P(z) &= 2\pi \int_0^\infty I r dr = 2\pi \text{Re} \left\{ \int_0^\infty \exp(ik\gamma z) \tilde{U}(\alpha) \gamma \alpha d\alpha \right\} \\ &= 2\pi \int_0^1 \tilde{U}^2(\alpha) r \alpha d\alpha, \end{aligned} \quad (7)$$

where

$$\tilde{U}(\alpha) = R J_1(k\alpha R) / \alpha, \quad (8)$$

is the angular spectrum of the initial condition. The second order moment beam width is

Fig. 4 The physical situation of the plane wave passing through a small circular aperture.

$$W^2(z) = \frac{4\pi}{P(z)} \int_0^\infty I r^3 dr$$

$$= \frac{\lambda^2}{\pi P(0)} \operatorname{Re} \left\{ \int_0^1 \frac{\partial [\tilde{U}(\alpha) \gamma \exp(ik\gamma z)]}{\partial \alpha} \frac{\partial [\tilde{U}(\alpha) \exp(-ik\gamma z)]}{\partial \alpha} \alpha d\alpha \right\}. \quad (9)$$

Selected the plane $z = 0$ as a reference plane, the beam width $W(z)$ follows a hyperbolic law of variation along z as

$$W^2(z) = W^2(0) + z^2 \tan^2 \theta_0, \quad (10)$$

where beam waist $W(0)$ and the far field divergence angle θ_0 are separately decided by

$$\frac{W^2(0)}{\lambda^2} = \frac{1}{\pi P(z)} \int_0^1 \frac{\partial [\tilde{U}(\alpha) \gamma]}{\partial \alpha} \frac{\partial [\tilde{U}(\alpha)]}{\partial \alpha} \alpha d\alpha, \quad (11)$$

$$\tan^2 \theta_0 = \frac{4\pi}{P(z)} \int_0^1 \tilde{U}^2(\alpha) \frac{\alpha^3}{\gamma} d\alpha. \quad (12)$$

Therefore, the optical beam quality of beam from small aperture is

$$M^2 = \frac{\pi}{\lambda} W(0) \tan \theta_0. \quad (13)$$

The beam waist $W(0)$, the divergence angle θ_0 and optical beam quality factor M^2 of beam from small aperture as functions of the radius R are shown in Fig. 5.¹⁵⁾

When light beam emerges from a subwavelength aperture, it diffracts in wide-angle direction. But, this limitation can be overcome by creating a periodic texture on the exit side of a single aperture in a metal film. The directionality of light emerging from the aperture can be controlled as a beam with a small angular divergence approximately $\pm 3^\circ$.¹⁶⁾ The radiating region is mainly confined to an area with lateral dimensions comparable to the wavelength of the light. When combined with enhanced

Fig. 5 Beam waist $W(0)$, divergence angle θ_0 and optical beam quality factor M^2 as functions of the aperture radius R . The blank circle means that the curve doesn't include this point.

transmission, this finding suggests that its photonic application is possible in various fields.

4. Equivalent optical beam qualities of quantum well laser beam

A Scheme of a 650 nm GaInP/AlGaInP multiple quantum well (MQW) laser is shown in Fig. 6. A 0.05 μm $(\text{Al}_{0.4}\text{Ga}_{0.6})_{0.5}\text{In}_{0.5}\text{P}$ /GaInP compressive strained MQW active layer is sandwiched between two $(\text{Al}_{0.4}\text{Ga}_{0.6})_{0.5}\text{In}_{0.5}\text{P}$ optical confinement layers. Only the laser diode (LD) core is used. The threshold current of this LD is 18 mA. Fig. 6 (a) and (b) describe observations of emission at the cleavage plane by using 1000 $\times$ microscope with oil. The horizontal direction x is parallel to the junction plane, and the vertical direction y is perpendicular to the junction plane. Fig. 6 (a) shows a emission pattern in the case of normal lasing with 28 mA and 3.2 mW, and the lasing is expanded to three layers. Fig. 6 (b) is that for weak lasing with 4 mA and 12 μW , and the lasing is confined only in an active layer.

As the quantum well laser beam has small beam waist and large divergence angles, it is difficult to directly measure its optical beam quality. Therefore, equivalent optical beam quality factor of LD beam is measured indirectly. First, the nonparaxial LD beam is collected nontruncatedly and transformed into paraxial one. Then, by measuring the beam waist and the corresponding far field distributions of paraxial beam, equivalent optical beam quality factor is determined. Here, the measurement of all beam widths adopts the moving slit method suggested by ISO.

A 3-mm Φ , 100 $\times$ 1.25 object lens of microscope is used with oil immersion to ensure that the truncation rate is lower than 1%.¹⁷⁾ Every thing is made very clear as shown in Fig. 7. The total coupling efficiency is 87 %, and the loss is caused by reflection and absorption by the transformation system. After trans-

Fig. 6 GaInP/AlGaInP MQW-LD structure and its emissions at the cleavage plane in cases of normal lasing (a) and weak lasing (b).

Fig. 7 Nontruncated nonparaxial transformation and equivalent optical beam qualities of MQW-LD beam compared with Gaussian beam of He-Ne laser.

formation at a distance 7.95 m away from the source, the horizontal beam waists are measured to be 0.3 mm for both of normal and weak lasing cases that correspond to (A) and (B) in Fig. 7. And the Rayleigh length is 0.44 mm. The vertical beam waists at the following same position, however, are measured to be 0.45 mm for (A) and 0.4 mm (B), respectively. The corresponding Rayleigh lengths are 0.98 m for (A) and 0.82 m for (B).

To measure the far field distributions, the observation distance should be longer than 7 times of Rayleigh length for each direction. Thus the divergence angles can be determined by measuring the far field beam width of transformed paraxial beam shown by the right most pictures of (A) and (B).

After calculations, the equivalent optical beam quality factors M_e^2 for normal lasing are 1.2 and 0.6 in the horizontal (x) and vertical (y) directions, respectively. While the corresponding M_e^2 for weak lasing are 1.6 and 0.3. As the position of the vertical beam waist is farther than that of the horizontal beam waist as shown in Fig. 7, the vertical equivalent optical beam quality is better than the horizontal beam quality. For the calibration, Fig. 7(C) shows beam patterns taken with Gaussian beam of 632.8 nm He-Ne laser. The accuracy of the data for the equivalent optical beam quality factors is about $\pm 20\%$. If the aberrations of the transformation lens are considered, the equivalent optical beam qualities of LD will be much better.

By applying the nonparaxial vectorial moment theory and the waveguide mode theory, the beam quality of quantum well laser can be theoretically analyzed.¹⁸⁻²⁰ The calculated results just support the experimental measured results described above.

5. Conclusions

New beam CO₂ lasers are in miniature production. When the basic principle is known very clearly, we will use this technique to generate new beams in other type lasers. Potential applications of light beam from a subwavelength aperture are to reduce the intrinsically high beam divergence of common optical devices such as semiconductor lasers and to optimize near field devices for microscope.¹⁶ Discovery of the fact that quantum well laser beams have initial nature of vertical optical beam quality factor being less than unity will promote the study of LD science and LD technology. Compact nonparaxially nontruncated and nonsymmetric optical transformer can be designed to make a symmetric and small beam,²¹ which can improve coupling efficiency of fiber and data storage density of VCD.

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