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Laser Diode Beam Basics, Manipulations and Characterizations

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Foreword

Many optical design technical books are available for many years. These books mainly deal with image optics design based on geometric optics and using sequential raytracing technique. Some books slightly touched laser beam manipulation optics design. Since the invention of a laser in 1960s, lasers find extensive applications in many areas. Among many types of lasers, laser diodes are unique for their many advantages, such as having a wide range wavelength and power selections, being small; high efficient and able to be modulated to gigahertz and operated by batteries. Because of these advantages, lasers diodes are widely used in fiber optical communications, data storage and read out, sensing and measurement, material processing, etc. Most of these applications require a laser diode beam to have certain size, shape, divergence, intensity distribution etc. In most cases, an optical system needs be built to manipulate the laser diode beam to meet all these requirements.

When design laser diode beam manipulation optics, special attention must be paid to the Gaussian nature of the beam, geometric optics raytracing technique must be modified to avoid causing errors. The Gaussian nature of laser beams is often overlooked by some scientists and engineers who don't have enough knowledge and experience in lasers. Laser diode beams are particularly difficult to manipulate, because these beams have very large divergent angles, are elliptical and astigmatic.

Many books on laser diodes have already been published. These books all extensively deal with laser diode physics with little touching on laser diode beam manipulations and characterizations. On the other hand, some internet resources dealing with laser diode beam manipulations can be found online. To the author's opinion these internet resources have not covered enough materials with enough details on laser diode beam manipulations and characterizations. A technical book concentrated on laser diode beam manipulations and characterizations can provide useful information to laser diode users. To the author's best knowledge, there is still no such a book available. This book tries to address this need.

This book is a summary of the author's many years' industrial experience in laser diode applications, is concentrated on the very practical side of the subject, and only discusses the basic physics and mathematics that are necessary for the readers in order to understand the subject. This book is intended to provide a practical guidance and reference to those scientists and engineers who are still new to laser diode applications, and to those undergraduate and graduated students who are studying lasers and optics. The author hopes the readers are able to fast and easily find the most practical and useful information about laser diode applications from this book without the need of searching through a sea of information. Since the term “laser optics” is often reserved for laser cavity optics, the term “laser beam manipulation optics” is used in this book to avoid possible confusion.

Contents

Chapter 1
Laser Diode Basics

Abstract The optical characteristics of laser diodes are summarized. The electrical, mechanical and temperature characteristics of laser diodes are briefly summarized. Vendors and distributors for laser diodes, laser diode modules, laser diode optics and laser diode characterizing equipment are introduced.

Keywords Laser diode · Transverse mode · Elliptical beam · Active layer · Gaussian profile · Divergence · Characterization

Laser diodes find wide applications in optical fiber communications, data recording and reading, sensing and measurements, material processing, etc., because laser diodes can offer wide range of wavelength selections from purple to infrared, are as small as needle tips, have high electrical to laser power conversion efficiency of over 30 %, can be operated by battery, and can be modulated to Giga hertz. However, laser diode beams have large divergences, elliptical shapes and astigmatisms, and therefore are difficult to manipulate compared with almost any other types of laser beams.

Laser diodes also have large manufacturing tolerances compared with other types of lasers. Therefore laser diodes of the same type can behave a little differently, in terms of wavelength, power, threshold, beam waist size, beam divergence, beam pointing etc. When we talk about parameter values for laser diodes in this book, we have to use terms such as "typical value" or "typical value range" because of the large tolerance.

There are many different types of laser diodes. Each type has its unique characteristics. A little bit background knowledge about laser diodes is necessary for the readers of this book to understand the contents of this book. Many books and internet websites can provide either in depth [1, 2] or general [3] knowledge about laser diodes. However, for the readers' convenience, we still need briefly introduce this background knowledge in this book without involving a lot of physics and mathematics.

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1.1 Active Layer

The beam of a laser diode is emitted from an active layer sitting on top of or buried inside a bulk inactive material, as shown in Fig. 1.1. The back facet of the active layer is high reflection (HR) coated, the front facet of the active layer is uncoated with a natural reflectivity of about 0.3. The two facets of the active layer form a lasing cavity. A laser diode with such a cavity is called "Fabry–Perot" laser diode, to be distinguished from laser diodes with other type cavities. The active layer has a refractive index higher than the refractive index of the bulk inactive material around it and acts as a waveguide.

Electrical current is injected into the active layer, where electrons and holes are combined to emit photons. The photons are bouncing forth and back between the two facets of the active layer to lase. The active layer is only a fraction of micron thick, because thicker active layer will result in lower lasing efficiency. Only portion of the laser energy is confined inside the active layer. The fraction of the laser energy confined inside the active layer is called "confinement factor". To increase the output laser power, the active layer can be made up to a few hundred microns wide. Such laser diodes are called "wide stripe" or "broad stripe" or "broad area" laser diodes. A wide stripe active layer can support more than one transverse (TE) lasing mode. The term "high power laser diodes" often refers to wide stripe, multi-transverse mode laser diodes. "Transverse mode" is a terminology frequently used to describe the intensity profile of a laser field that is supported by a certain waveguide. One laser beam can contain single TE mode or multi TE modes. For single TE mode beam, the mode is the beam, the mode structure is the beam structure. The laser beam shown in Fig. 1.1 is a single TE mode beam. Because multi TE mode laser beams cannot be well collimated or focused to small spots, the active layer widths are often limited to within a few microns in order to limit the mode numbers to single TE mode. The small widths of active layers limit the emitted laser power to below 100 mw or so, depending on the laser diode type and wavelength. Since the beams of most laser diodes are emitted from the edge of the active layers, these laser diodes are also called "edge emitting" laser diodes. Laser diodes are also called diode lasers or semiconductor lasers.

In the early years of laser diode development, the active layer confined the laser field by optical gain induced index variation in the active layer, such laser diodes are called "gain guided" laser diodes. Gain guided laser diodes have lower efficiency, tends to have more transverse modes, are less stable, and are no longer produced. Nowadays, the active layers of laser diodes have refractive index higher than the index of the surrounding bulk materials. Such laser diodes are called "index guided" laser diodes. There are many different types of active layer structures, such as "quantum well", "multi-quantum well", "hetero structure", "ridge" etc. All these active layer structures are developed in order to increase the lasing efficiency as well as the laser power of the laser diodes. The laser beams emitted from these different types of laser diodes have no systematic differences.

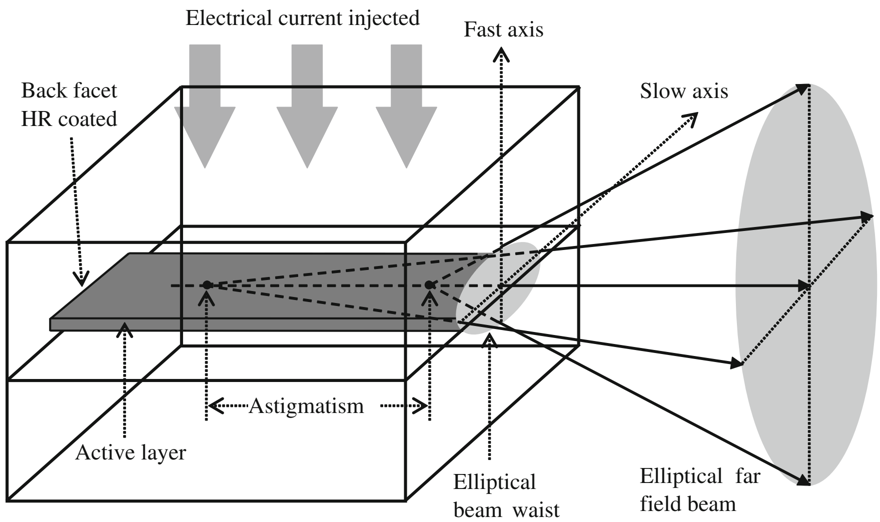

Fig. 1.1 A laser diode has a thin active layer. The emitted laser beam shown here contains single transverse mode, is elliptical, highly divergent and astigmatic. The astigmatism magnitude is much exaggerated for illustration

Laser diode users don't need care a lot about the active layer structures and materials, a good understanding of laser diode beam characteristics would be adequate.

Laser diode technologies are under fast developing, the knowledge about laser diodes is updated frequently.

1.2 Single Transverse Mode Laser Diode Beams

1.2.1 Elliptical Beam

Single TE mode laser diode beams have quasi Gaussian intensity profiles and are most widely used. The active layers of laser diodes have rectangular shape cross sections. When operated, portion of the laser fields will leak out of the active layers to make beams emitted from the active layer elliptical, as shown in Fig. 1.1. The beam waist diameters are about one micron in the direction vertical to the active layer and a few microns in the direction horizontal to the active layer, as shown in Fig. 1.1. The beam elliptical ratio is typically from 1:2 to 1:4. The beam far field divergence is also different in the vertical and horizontal directions with a typical ratio of 2:1–4:1. Because the beam divergence is larger in the vertical direction, this direction is often called "fast axis" direction. Then the horizontal direction is called "slow axis" direction, as shown in Fig. 1.1. As the beam propagates, the beam size in the fast axis direction will surpass the beam size in the slow axis direction, the beam shape will become vertical elliptical, as shown in Fig. 1.1. This phenomenon is unique to laser diode beams and will be discussed later in this book. An elliptical shape beam is one of the undesired characteristics of laser diodes. Several types of optical components have been developed to circularize the elliptical beams.

1.2.2 Large Divergence

The divergence of single TE mode laser diode beams can vary significantly from different types of laser diodes and even vary from diode to diode of the same type. The typical full width half magnitude (FWHM) divergent angle is about 15–40° and 6–12° in the fast and slow axis directions, respectively. Laser diode industry traditionally uses the FWHM divergent angle to specify the beam divergence. While in optical industry, the $1/e^2$ intensity divergence is often used. The later is about 1.7 times larger than the former.

Because of the very large divergence in the fast axis direction, the lens used to collimate or focus a laser diode beam must have at least one aspheric surface to correct the spherical aberration and a numerical aperture of at least 0.3 to avoid severe beam clipping. Although a lens with numerical aperture of 0.6 will still clip the beam. Many aspheric lenses specially designed and fabricated for collimating laser diode beams are available in market with numerical aperture ranging from 0.3 to 0.6; that means laser diode beams will still be more or less clipped in the fast axis direction. Clipping on a beam will cause side lobes and focal shift to the beam, and increased divergence of the beam. The large divergent beam is another undesired characteristics of laser diodes.

1.2.3 Quasi Gaussian Intensity Profile

The shape or structure of the TE modes in a laser diode beam is mainly determined by the structure of laser diode active layers. Waveguide theory tells us that rectangular waveguide TE modes are not exactly Gaussian modes. The structure of active layers can be complex and different for different types of laser diodes. The gain inside the active layer and the loss outside the active layer will also affect the mode shapes. Therefore, the modes of most singe TE mode laser diodes are somehow different from Gaussian modes [4]. To the best of the author's knowledge, no commonly accepted relationship linking laser diode type to transverse mode shape has been established, only individual case studies have been reported. The central parts of laser diode TE modes are usually similar to Gaussian profiles, the edge parts of the modes are not, with either longer or shorter tails compared with the tails of Gaussian modes, as shown in Fig. 1.2. A real observed beam

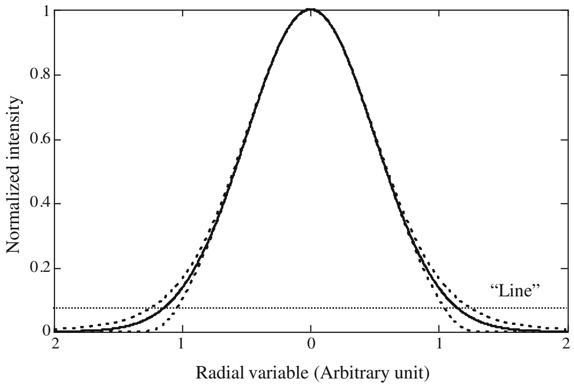

Fig. 1.2 The solid curve is a gaussian mode. The two *dash* curves are two quasi gaussian modes with their central parts near gaussian, but longer or shorter tails than gaussian. The real observed intensity profile of a laser diode beam often looks like the portion *above* the "Line"

intensity profile of a laser diode often looks like the part above the "Line" in Fig. 1.2, the bottom few percent of the profile appear to be cutoff. This phenomenon may be caused by the complex structure of the active layer of the laser diodes.

Single TE mode laser diode beams are often approximated by Gaussian modes, because the characteristics of Gaussian modes are simple and well understood. Such approximations are usually accurate enough for most applications.

1.2.4 Astigmatism

Laser diode beams are astigmatic; that is a result of the rectangular shape waveguide (active layer) and the gain profile varying across the active layer in the slow axis direction. As shown in Fig. 1.1, the waist of a laser beam in the fast axis direction is located at the facet of the active layer, the waist in the slow axis direction is located behind the waist in the fast axis direction. The astigmatism illustrated in Fig. 1.1 is much exaggerated for clarity. Similar to other laser diode parameters, astigmatism value varies from different types of laser diodes and from diode to diode of the same type. For single TE mode laser diodes, the astigmatism is usually from 3 to 10 μm. For multi TE mode laser diodes, the astigmatism is usually from 10 to 50 μm. From the application point of view, there is no need to study the origin of the astigmatism, we are more interested in measuring and correcting the astigmatism.

Astigmatic beams is another undesired characteristics of single TE mode laser diodes. Several types of optical components have been developed to correct astigmatism. We will discuss measuring and correcting astigmatism in Sects. 5.4 and 3.4, respectively. Since the beams of multi TE mode laser diodes cannot be well collimated or focused to a small spot, astigmatism in these beams is of low importance.

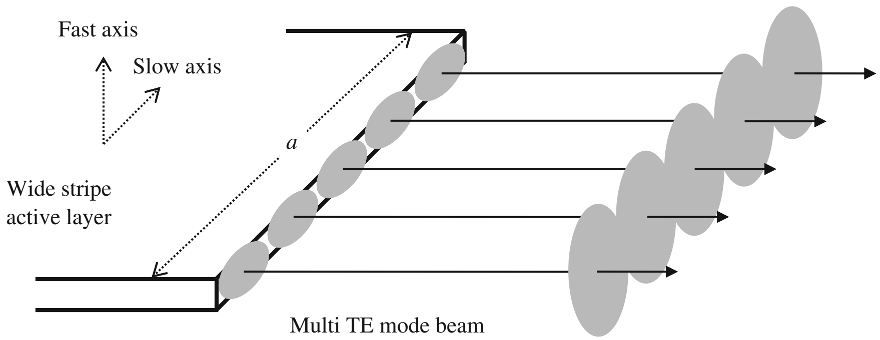

Fig. 1.3 The beam of a wide stripe laser diode contains multi TE mode

1.2.5 Polarization

Laser diode beams are linear polarized. The polarization ratio is high from 50:1 to 100:1 for Single TE mode laser diode, and around 30:1 for wide stripe multi TE modes laser diodes. The polarization is in the slow axis direction. The high polarization ratio of laser diode beams can either be an advantage or disadvantage, depending on the type of applications. As a comparison, most HeNe laser beams are randomly polarized.

1.3 Multi Transverse Mode Laser Diode Beams

1.3.1 Wide Stripe Laser Diode Beams

To maintain the lasing efficiency, the active layer thickness cannot be increased. The only way to increase the laser power is to increase the active layer width. For laser diodes with power higher than 100 mW or so (depends on the laser diode type and wavelength), the active layer widths are tens of microns or even up a few hundred microns. Such laser diodes are often called wide stripe laser diodes. The beam emitted from a wide stripe active layer contains multiple TE modes as shown in Fig. 1.3, every TE mode is a quasi Gaussian mode. All these modes combines to form a beam called multi TE mode beam. As the beam propagates, every mode increases its size and gradually merges together to form a light line in the slow axis direction, as shown in Fig. 1.3.

Figure 1.4 shows the spatial intensity distribution of five TE modes at three different propagation distances. Figure 1.4a shows the intensity distribution at or near the laser diode facet. As the beam propagates, the sizes of the five modes increase, the modes gradually merge together as shown in Fig. 1.4b and c by the thin curves. The intensity distributions of the five modes combined are shown in Fig. 1.4b and c by the thick curves. When we scan such a multi TE mode beam,

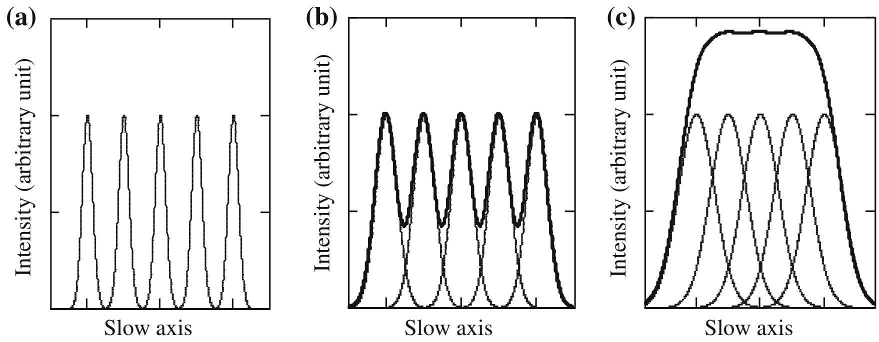

Fig. 1.4 The thin curves are for the spatial intensity distributions of five TE modes at three propagations distances. **a** At or near the diode facet. **b** At several microns. **c** At tens of microns and beyond. The thick curves are the five modes combined spatial intensity distribution

the scan head is usually at least several millimeters away from the laser diode, the scan result will be something similar to that shown in Fig. 1.4c. However, such a beam is not a true flat top beam. When the beam is focused, the intensity profile of the focused spot will be like that shown in Fig. 1.4a if the focusing lens is of high quality, or like that shown in Fig. 1.4b if the focusing lens has aberration that will increase the size of the mode image.

The beams of wide stripe laser diodes are not like the laser beams we often see, rather are somehow like the lights from a light bulb. These beams cannot be well collimated focused to a small spots. We will discuss this issue in detail in Chap. 4.

1.3.2 Laser Diode Stack Beams

Several wide stripe active layers can be stacked up to further increase the laser power. Such a laser is called laser diode stack. Figure 1.5 shows a four layer laser diode stack. There are many different combinations of active widths and stack layers. The power of a laser diode stack can be up to thousands watts. A laser diode stack can be treated as a rectangular shape light source with size of $a \times b$ as shown in Fig. 1.5.

The beams of laser diode stacks are not like the laser beams we often see, rather are somehow like the lights from a light bulb. These beams cannot be well collimated or focused to a small spots. We will discuss this issue in detail in Chap. 4.

1.4 Laser Diode Spectral Properties

There are many different types of laser diodes, using different gain materials and different active layer structures. Even for the same type of laser diodes, the manufacturing tolerances can cause laser diodes behaving differently from each

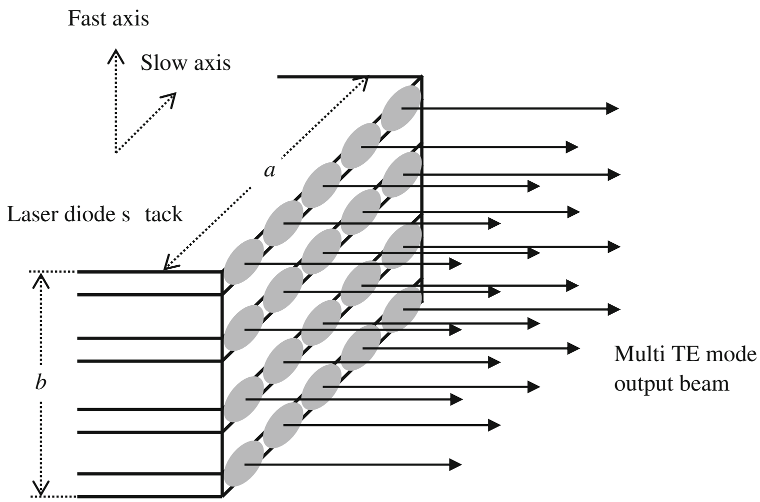

Fig. 1.5 Schematic of a laser diode stack

other. The situation for laser diodes are far more complex than many other type of lasers.

1.4.1 Longitudinal Modes

The two facets of the active layer of a laser diode form the lasing cavity. The optical length of a cavity is given by *nL*, where *n* is the refractive index of the active layer material and *L* is the physical length of the cavity, as shown in Fig. 1.6. *n* is typically between 3 and 4, and *L* is typically a fraction of millimeter, therefore *nL* can be estimated to be 1 mm. A cavity allows many standing optical waves or longitudinal modes to exist in it. Figure 1.6 shows two standing waves as an example. It's noted that longitudinal mode is often abbreviated as "mode", but it means a laser field with certain wavelength. While a "TE mode" is also often abbreviated as "mode", but it means a laser field with certain spatial structure.

Laser diode active mediums have a Gaussian or Lorentz type gain profile. Only those longitudinal modes inside the gain band are amplified by the active medium, as illustrated in Fig. 1.7. Laser gain comes from the carriers provided by the injected electrical current, and the carrier numbers are limited. The longitudinal mode being closest to the gain peak has the largest gain and is the strongest mode. The strongest mode consumes more carriers than the other modes do and leaves less carriers for other modes to consume. That puts the strongest mode in a more advantage position. The more advantage position allows the strongest mode to consume even more carriers. This circle is going on and eventually all the other modes are extinguished. Such a phenomenon is called "mode competition". Mode

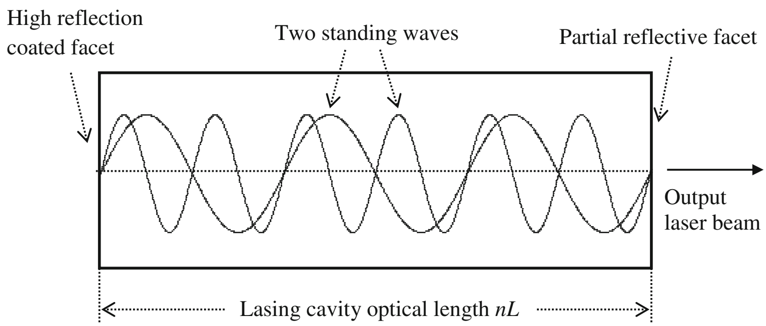

Fig. 1.6 Illustration of standing waves in a laser cavity

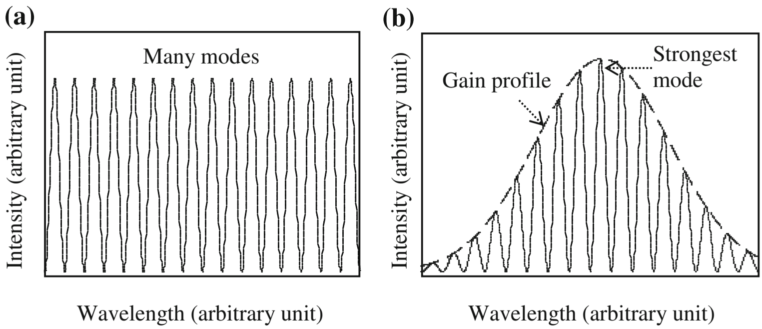

Fig. 1.7 **a** A laser cavity can support many longitudinal modes. **b** Only those longitudinal modes inside the gain profile are supported by the active medium

competition makes most laser diodes can operate with single longitudinal mode or single wavelength, that is a good news for laser diode users. However, multi longitudinal mode operation is not rare for laser diodes, particularly at low power level. The mode spacing or wavelength difference between the two neighboring modes is about 1 nm.

1.4.2 Wavelength

Laser diode wavelength ranges from violet to infrared. The wide wavelength selection is one of the major advantages of laser diodes over other types of lasers. Because of the manufacturing tolerance, laser diodes usually have a wavelength tolerance of ±5nm or so. Laser diode users should be fully aware of this. If they want a more accurate wavelength, they can ask laser diode vendors to select these laser diodes with the right wavelengths for them with a premium.

As we can see from Fig. 1.6 that the wavelength of a longitudinal mode is proportional to the optical length of the cavity *nL*. The refractive indexes of the active mediums is a function of carrier density or inject current, the wavelength thereby can be changed by changing the injection current, a typical changing rate is $d\lambda/dI \approx 0.01$ nm/mA. Thermal expansion of the active layer will also change the wavelength.

As the temperature of the active layer or the injection current to the active layer changes, the gain profile does not move much, the longitudinal modes will shift their positions relatively to the gain band. The strongest mode may gradually move away from the gain peak and another mode may gradually move towards the gain peak. After passing through a critical point, the other mode becomes dominant and extinguishes the previous strongest mode. This phenomenon is called "mode hopping". Sometimes, a laser diode is operated at such a state that two modes are equally close to the gain peak, a small perturbation in temperature and/or current can tip the balance, repeated mode hopping between these two modes will occur. Mode hopping not only change wavelength, laser power and even beam spatial profile are also slightly affected. Continuous mode hopping is annoying and should be avoided by slightly adjusting the temperature or injection current of the laser diode.

Some commonly used laser diode wavelengths are listed below.

375 nm	405 nm	445 nm	473 nm	485 nm	510 nm	635 nm
640 nm	657 nm	670 nm	760 nm	785 nm	808 nm	848 nm
980 nm	1,064 nm	1,310 nm	1,480 nm	1,512 nm	1,550 nm	1,625 nm
1,654 nm	1,877 nm	2,004 nm	2,330 nm	2,680 nm	3,030 nm	3,330 nm

Since laser diode technology is progressing fast, the wavelength selection range can be extended any time. Laser diode users should check the latest development in this field.

1.4.3 Linewidth

Laser theory tells us that laser linewidth is inversely proportional to the cavity optical length. Laser diode cavities have a short optical length of about 1 mm, that means a large linewidth. The refractive index of the active layer material is a function of inject current or carrier density, the coupling effect between the index and carrier density is called "linewidth enhancement factor α", α has a value between 2 and 7. It has been shown that laser diode linewidth will be further increased by a factor of $1 + \alpha^2$. There are also other types of noises to increase the linewdith. All these factors add up makes the linewidth of laser diodes much larger than the linewidth of other types of lasers. A typical value of laser diode linewidth is $\Delta\lambda \sim 0.1$ nm. The coherent length ΔL of a laser diode beam is related to its linewidth by $\Delta L = \lambda^2/\Delta\lambda \sim 10$ mm, if we assume the wavelength is $\lambda \approx 1$ μm. The short coherent lengths of laser diode beams limit their interference related applications.

Two special types of laser diodes have been developed to reduce the linewidth as well as to ensure operating at single longitudinal mode.

1. Distributed feedback (DFB) laser diodes. This type laser diodes have a refractive index grating build into the active layer in the longitudinal direction, the grating favors one longitudinal mode, depress all other longitudinal modes and can significantly reduce the linewidth by an order or much more.
2. Distributed Bragg reflector (DBR) laser diodes. This type of laser diodes have a refractive index grating reflector build at the end of the active layer, the reflector will selectively reflects only one longitudinal mode and reduce the linewidth by an order or much more.

1.5 Laser Diode Power

1.5.1 Continuous Wave Operation

Laser diodes can output continuous wave (CW) laser powers ranging from a few milliwatts for a single TE mode laser diode to several kilo watts for a laser diode stack. The electrical to laser energy conversion efficiency of laser diode is in the range of 0.5 mW/mA. The conversion efficiency drops as the temperature of the laser diode rises, the efficiency changing rate is about one percent per degree C^o.

A typical laser power versus electrical inject current curve looks like that shown in Fig. 1.8a, this curve is called $L \sim I$ curve. When the current is below the threshold, a laser diode only has spontaneous emission; that is a weak and wide spread light with the same wavelength of the laser light. The spontaneous emission intensity slowly increases as the current increases. At the threshold, the lasing gain equals to the sum of all the losses, such as material absorption loss, cavity loss, etc. When the injection current is above the threshold, the laser diode starts lasing, the laser power increases fast as the current is increased. As the current continues increases, the laser power increment rate will slow down, the laser power reaches its saturation level, as shown in Fig. 1.8a. The specified power level should be below the saturation power level. Further increasing the current will blow out the laser diode. Users of laser diodes should slowly increase the current till the laser power reaches the level specified by the datasheet to avoid overdrive the laser diode. One second of overdriving can partially or totally blow out the laser diode. The threshold current level is from tens to hundreds of milliamperes for different types of laser diodes. Again, different laser diodes of the same type can have tens of percent threshold current difference and tens of percent difference in $L \sim I$ curve slope.

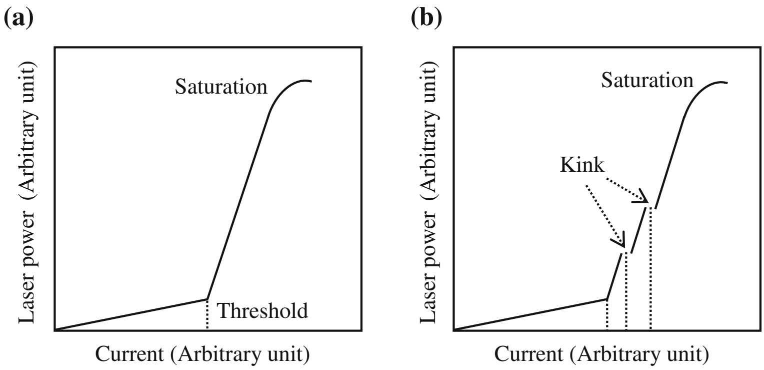

Fig. 1.8 **a** A typical $L \sim I$ curve. **b** A $L \sim I$ curve with two kinks

Sometimes, a $L \sim I$ curve has kinks, as shown in Fig. 1.8b. Kinks are a phenomenon of longitudinal mode hopping, because changing current will change the optical length of the laser cavity and cause mode hopping or kink. For CW applications, the laser current should be adjusted away from the kink point. For modulated applications, the current swipes over a range that might cover the kink points, then kinks may affect the applications. Some laser diodes are kink free within their specified operation ranges.

Laser diode active layer has a tiny volume of 100 μm^3 or so, the electrical current density and laser power density are very high inside such a small volume, the high laser power density is the main cause of laser diode damage.

1.5.2 Modulated or Pulsed

Laser diode can be modulated by modulating the injection current. When the injection current is changed, the laser field takes several round trips inside the laser cavity to establish the new operation state. The time needed to make these several round trips sets the theoretical maximum modulation rate for a laser diode. For a laser cavity with 1 mm optical length, one round trip inside the cavity takes 2×1 mm/3×10^8 m s^{-1} $\approx 7 \times 10^{-12}$ s, several round trips takes $\sim 10^{-11}$ s, the practically achieved maximum modulation rate is then about $\sim$GHz. Such a frequency is mainly used in fiber optic telecommunications. In most other applications, megahertz modulation speed will be fast enough and is comfortable to laser diodes.

Laser diodes can also be pulsed. The smallest pulse width and the highest repetition rate are limited in a way similar to the limitation on the maximum modulation rate. There are many types of laser diodes specially designed for pulsed operation, the typical pulse width and duty cycle is 100 ns and 0.1 %, respectively. Pulsed operation allows the laser diodes to output a peak power much higher than the average power CW operation allows. When used in ranging application, laser diodes are pulsed. Pulsed Electrical power sources are required to pulse the laser diodes. Pulsed laser diode modules have special electronics built in the modules, the electronics can take in CW electrical power and output electrical pulse.

1.6 Temperature Effect

Laser diode operation states are affected by temperature change. High operation temperature will not only reduce the efficiency, but also reduce the lifetime of laser diodes at a rate of a few percent per degree C^o. Thermal expansion of the cavity can increase the wavelength, with a typical change rate of $d\lambda/dT \approx 0.2$ nm/C^o for visible wavelength and $d\lambda/dT \approx 0.3$ nm/C^o for infrared wavelength. Temperature change will change the value of current at which a kink occurs. Low power laser diode packages have a metal base of about 100 mm^3 volume in it. This metal base is the mounting support as well as a heat sinker, and should be in thermal contact with a larger heat sinker. Laser diode chip is tiny; its temperature can be measured by measuring its IR spectrum, that is not an easy measurement. Laser diode temperature is commonly monitored and controlled by monitoring and controlling its heat sinker temperature. As the temperature of a laser diode rises, the maximum inject current allowed or the maximum laser power drops. A driving current safe at lower temperature may be too large at higher temperature. Therefore, many laser diode modules have temperature stabilization functions.

If proper protection procedures are taken, laser diode lifetime can be very long, of the order of 10,000 h.

1.7 Electrical Properties of Laser Diodes

A laser diode can be driven by a DC power source of about 2 V or higher. Laser diode datasheet should specify the power source voltage. Laser diodes are very vulnerable to electrical static discharge. The work station and the person handling laser diodes should be properly grounded. Otherwise, a laser diode can be damaged without any noticeable sign. Laser diode are also vulnerable to surges in the injection current, should be driven by a current source or batteries through a protective circuit or by a special power supply. Once a laser diode is mounted in a module, it’s safe to handle the module by ungrounded hands or tools, the module housing will shield the laser diode inside from electrical static discharge, and is safe to operate the module by conventional power source; the electronics inside the module will protect the laser diodes from power surge.

The internal circuit of laser diodes can be slightly different for different types of laser diodes. Figure 1.9 shows three typical internal circuits. Laser diodes are operated by applying current in forward direction. The photodiode in the internal circuit is physically mounted behind the back facet of a laser diode active layer to

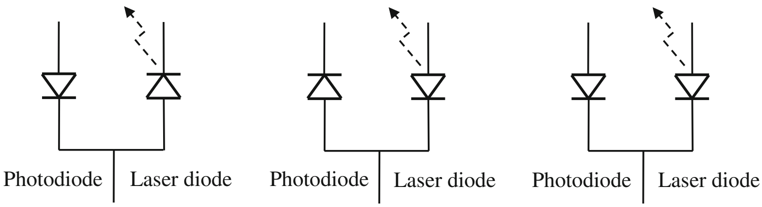

Fig. 1.9 Three types of laser diode internal circuit

pick up the laser power leaking through the HR coated back facet. The photodiode output current is proportional to the laser power and is used as a feedback in a circuit loop to stabilize the laser power. It's noted that a laser diode module cannot be simultaneously operated at power stabilized mode and current stabilized mode without temperature control. Because at a constant current level, temperature change will change the laser power, or at a constant power level, temperature change requires different current. Power stabilization is one of the basic functions of laser diode modules.

Laser diodes users should check the datasheet to find how the internal circuit is connected to the pins of the package.

1.8 Vertical Cavity Surface Emitting Lasers (VCSEL)

VCSEL is a unique type of laser diode, as shown in Fig. 1.10. Two Bragg reflectors form a lasing cavity, a circular window is itched on one Bragg reflector to let the laser beam output. The output beam is thereby circular. Circular shape beams is the main advantage of VCSELs. The lasing cavity length equals to the thickness of the active layer and is very short, the laser field does not have a lot gain before the field outputs from the cavity, the laser power can only be a few milliwatts, that is the main disadvantage of VCSELs. The only way to increase the laser power is to increase the window size. However, large window size will make the output beam have multi TE modes and takes away the only advantage of VCSELs.

1.9 Manufacturing Tolerances

Laser diodes have manufacturing tolerances much larger than the tolerances of other types of lasers. In previous sections we have already mentioned that laser diodes have a wavelength tolerance of several nanometers, a beam divergence tolerance of a few degrees, a threshold current tolerance of tens of percent, and a $L \sim I$ curve slope tolerance of tens of percent. Besides these tolerances, laser diode chips also have mechanical mounting tolerance of about ±0.1 mm in all the three directions inside the laser cap, and a pointing tolerance of about $\pm 0.2^{o}$.

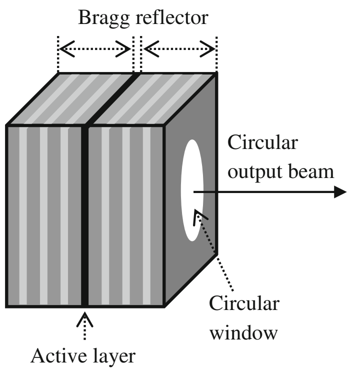

Fig. 1.10 Schematic of a VCSEL

When assembling a laser diode module, the laser diode chip need be positioned at the focal point of the collimating lens; the chip must point at the lens optical axis direction. Even we can align the laser diode cap well with the collimating lens; the laser diode chip inside the cap may not necessarily be aligned well with the lens because of all these mechanical tolerances. Some type of position and pointing adjustment mechanisms must be applied to the laser diode cap. As the laser diode cap position and pointing direction is being adjusted, the far field beam pattern and beam position must be monitored. The alignment is done when the far field beam pattern is clean and symmetric like the one shown in Fig. 3.4a, and the far field beam pattern is centered with a target its position was aligned before.

1.10 Laser Diode Packages and Modules

1.10.1 Laser Diode Packages

Lower power laser diodes have two standard packages of 9 and 5.6 mm, as shown in Fig. 1.11. The laser diode chip is mounted inside the caps. The two packages have the same shapes and proportions, only the sizes are different. The caps are filled with inertial gas and sealed. The inertial gas will significantly slow down the oxidization of the laser diode facet caused by the high laser power density. There is a sub millimeter thick glass window on top of the cap to let the laser beam shot out, as shown in Fig. 1.11. The cap size has nothing to do with the power of the laser diode chip in it. The metal base of laser diode caps serves as mounting support as well as a heat sinker.

There is no standard package for high power laser diodes or laser diode stacks. So, don't be surprised to see packages with various different shapes, structures and sizes. Figure 1.12 shows some of the packages. High power laser diodes sometimes require additional cooling besides the heat sinkers coming with the packages.

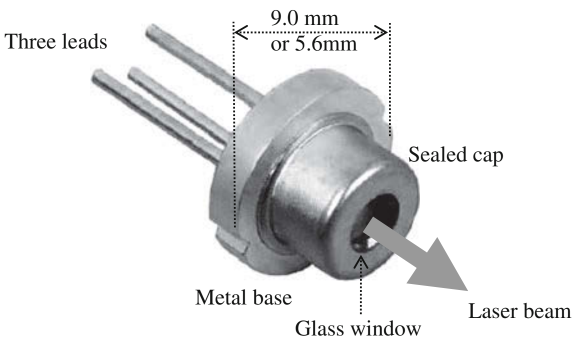

Fig. 1.11 Standard low power laser diode package

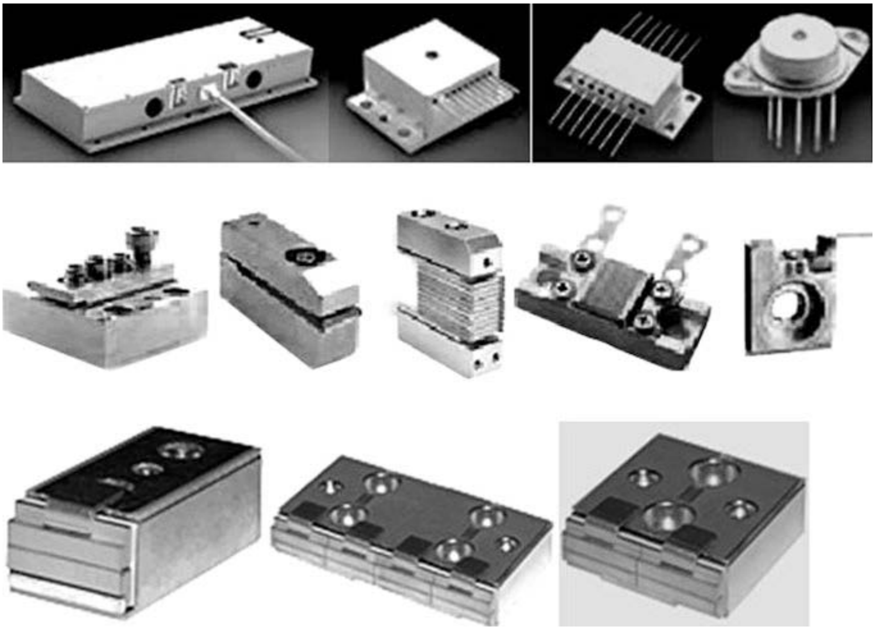

Fig. 1.12 High power laser diodes have various types of packages

1.10.2 Laser Diode Modules

Since the beams emitted by laser diodes have high divergence and are difficult to manipulate, and laser diodes are venerable to static discharge, laser diodes are often sold as modules. Laser diode users only need deal with the modules instead of dealing directly with laser diodes. A typical laser diode module contains at least three basic components; a laser diode, a collimating lens, and a circuit board. These three components are sealed in a rigid metal tube with two or more wires for

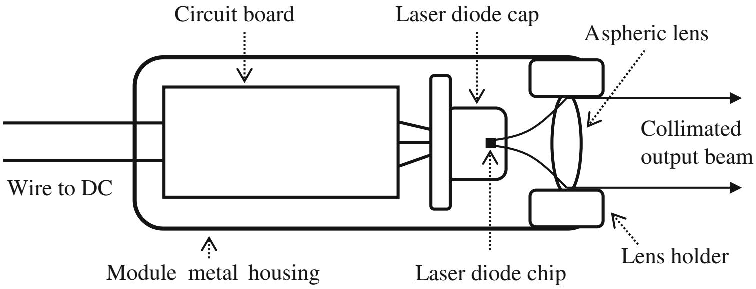

Fig. 1.13 Schematic of a most basic laser diode module

connecting the laser diode module to an electrical power source, as shown in Fig. 1.13. The lens collimates the laser diode beam so that laser diode users can have a collimated beam to work with. The circuit board has at least a laser power stabilizing function utilizing the output of the photodiode mounted behind the laser diode. Some laser diode modules also have inject current stabilizing function, The circuit board also shield the laser diode from electrical surge in the power source. The metal houses of laser modules are electrically grounded to protect the laser diode inside from static discharge. The collimating lens may be movable along the optical axis to provide adjustable focusing capability. The circuit board may have modulation or pulsation or even programming functions. The module may have an electrical fan attached to it to provide air cooling.

Laser diode vendors offer a wide selections of laser diodes, collimating lenses and some selections of circuit boards for the users to choose from, they will assemble the modules to best fit the user's needs. Buying a laser diode module may cost twice more than buy these three components separately and assemble them by the user self, but can save the user a lot time and effort.

1.11 Vendors and Distributors for Laser Diodes, Laser Diode Modules, Laser Diode Optics and Laser Diode Beam Characterizing Equipment

1.11.1 Laser Diode Vendors

Fabrication of laser diode chips require expensive equipment and tight process control. Laser diodes produced by brand name companies are of much higher quality, particularly have much longer life time, and can cost twice more than those laser diodes produced by unknown companies. In most applications, brand name laser diodes are worth the price. It's not a pleasant experience to stop the work and have a service personnel coming to fix the equipment because the laser diode in the equipment is blown out. Here is an incomplete list of brand name laser diode manufacturers:

Hitachi	Toshiba	Rohm	Mitsubishi	Sony
Hamamatsu	JDS Uniphase	Coherent	Opto Power	Applied Optronics
Opnext	Dilas Diodenlaser	Frankfurt Laser Company	Sacher Lasertechnik	Jenoptik

Nowadays, low power laser diodes are produced in millions, the unit price can be as low as a few dollars. Laser diode manufacturers usually no longer retail sell their laser diodes. In steady, they whole sell their laser diodes to distributors. If you want to buy low power laser diodes, you should first try to contact distributors. Here is an incomplete list of distributors:

Edmund Optics	Power Technology	Thorlabs	Lasermate
Blue sky Research	Lasertel	Digi-Key	

High power laser diodes are used in more special applications by much smaller quantities. The unit price can be high and the manufacturers usually do retail sales. Distributors also sell many high power laser diodes.

1.11.2 Laser Diode Module Vendors

The task of assemble laser diode modules is much easier than fabricate laser diode chips. Therefore the brand reputation is not as important for laser diode module manufacturers. Laser diode module manufacturers all sell their modules. Distributors sell some commonly used laser diode modules too. Users are recommend to buy laser diode modules directly from the manufacturers because the manufacturers can provide much insightful technical consulting to help the user to choose the right modules and provide better after sale support for their products. Here is an incomplete list of laser diode module manufacturers:

Power Technology	Micro Laser System	Coherent	Lasermate
Blue Sky Research	CVI Melles Griot	Lasertel	Point Source

1.11.3 Laser Diode Optics Vendors

The most widely used lens for collimating or focusing laser diode beams are produced by LightPath Inc.. They have two main product series. One series is the molded glass aspheric lens specially designed and fabricated for collimating laser diode beams. This lens series were produced by a company named Geltech Inc. and later acquired by LightPath. LightPath still uses Geotech lens to name this lens series. This series lenses are the most widely used lenses for laser diode beam manipulations, are of higher price compared with other brand lenses, and costs from $50 to $100 per lens. Another lens series produced by LightPath is called Gradium lens, these are gradient index lenses. The refractive index of these lenses radially varies with the index peaking at the optical axis of the lens and gradually dropping towards the edge of the lens. The gradient index of the glass combined with the spherical surface of the lens can effectively reduce the spherical aberration suffered by conventional spherical lenses. Another company named Foton Inc., a spin-off of Nippon Sheet Glass, produces gradient index lens too under the brand name of SelFoc lens. Gradient index lenses are usually of lower cost and lower quality compared with Geltech lenses. Besides the manufacturer LightPath Inc, some distributors sell the Geotech series lenses. Here is an incomplete list of distributors:

Edmund Optics	Thorlab	Power Technology

Some companies, such as CVI Melles Griot, Newport and Universe Kogaku (America) make multi elements lenses for collimating laser diode beams. These lenses consist of several spherical lenses and have high quality. Buyers should contact these companies directly for detailed information. There are some other brand lenses, aspheric or multi element spherical, for laser diode beam collimations.

It's note that there are many different aspheric lenses in market. Most of them are designed for other applications and will not well collimate laser diode beams. Users should be fully aware of this fact and only use those lenses specially designed for collimating laser diode beams.

1.11.4 Laser Diode Beam Characterizing Equipment Vendors

Laser diode beam characterizing equipment includes beam profilers, laser power meters and energy meters, wavelength meters (wavemeters) and spectral analyzers. Beam profilers can be used to characterize other types of laser beams, but they are mainly used to characterize laser diode beams because laser diode beams have a wide variety of shapes and divergences. The use of beam profilers will be discussed in Chap. 5. Laser power and energy meters used for laser diodes can be used for other types of lasers as well.

There are some high accuracy laser wavelength meters in market that can provide a measurement accuracy of 0.001–0.0001 nm, for example the wavelength meters made by Bristol Instruments (formerly Burleigh). These wavelength meters are expensive and require careful align the beam or coupling the beam into a single mode fiber during measurement. These wavelength meters are overkills for measuring laser diode beams since laser diode beams have wide linewidths and their wavelength vary with temperature and current. Wavelength meters with a measurement accuracy of 1–0.1 nm would be adequate for measuring laser diode beams, for example the simple wavelength meter made by Coherent Inc. This wavelength meter contains three single element detectors with three different spectral responses; the software in the wavelength meter will compare the output signal levels of the three detectors to calculate the wavelength of the beam being measured to an accuracy of 1 nm. The measurement process is very simple, only requires shooting the beam to be measured on the detector head. Coherent Inc. also sells another type wavelength meter with an accuracy of 0.005 nm. A monochromater or spectral analyzer can also be used to measure the wavelength of laser diode beams.

There are several companies sell various laser beam characterizing equipment. Among them, Coherent Inc. offers wide selections of beam profilers and beam analyzers, power meters and energy meters, and wavemeters. To the author's opinion Coherent Inc. is the first company buyers should check with.

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Chapter 2
Laser Diode Beam Propagation Basics

Abstract Laser diode beam propagation characteristics, the collimating and focusing behaviors and the M^2 factor are discussed using equations and graphs. Thin lens equation modified to be applicable for laser beams is introduced. An example about collimating and focusing a laser diode beam is presented. Raytracing technique is briefly discussed.

Keywords Thin lens equation · Propagation · Collimating · Focusing · Beam spot · Gaussian beam · Geometric rays

To understand laser diode beam propagation characteristics, some basic knowledge about laser beam propagation theory is necessary.

2.1 Basic Mode Gaussian Beam

Most laser beams have a circular shape cross section with a Gaussian intensity profile. Such beams are basic TE mode Gaussian beams. The characteristics of a Gaussian beam are described by a set of three equations [1].

$$w(z) = w_0 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \tag{2.1}$$

$$R(z) = z \left[1 + \left(\frac{\pi w_0^2}{\lambda z} \right)^2 \right] \tag{2.2}$$

$$I(r, z) = I_0(z) e^{-2r^2/w(z)^2} \tag{2.3}$$

where z is the distance from the waist of the laser beam, λ is the wavelength, w_0 is the $1/e^2$ intensity beam waist radius, $w(z)$ is the $1/e^2$ intensity beam radius at z,

H. Sun, *Laser Diode Beam Basics, Manipulations and Characterizations*, SpringerBriefs in Physics, DOI: 10.1007/978-94-007-4664-0_2,

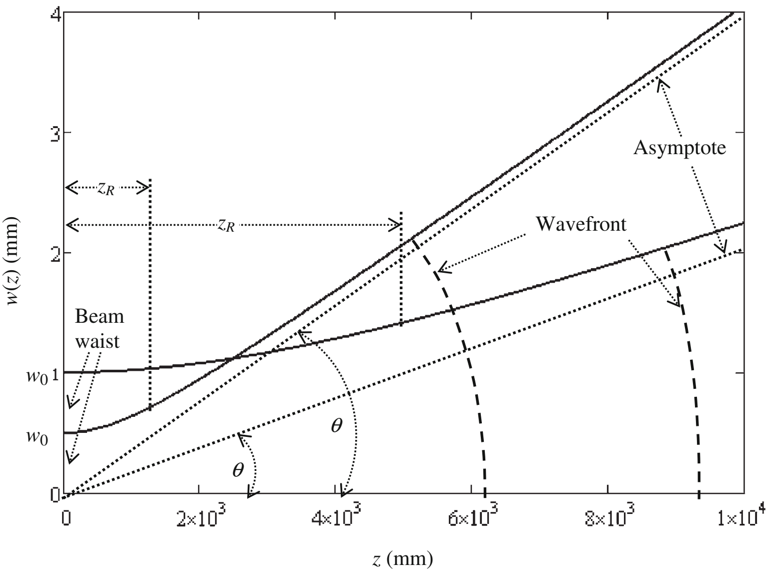

Fig. 2.1 The *thick curves* are $w(z)$ versus z for two laser beams with $w_0 = 1.0$ and 0.5 mm, respectively

$R(z)$ is the beam wavefront curvature radius at z, $I_0(z)$ is the beam peak intensity in a cross section plane at z, r is the radial coordinate in a cross section plane at z, and $I(r,z)$ is the beam intensity radial distribution in a cross section plane at z. Figure 2.1 shows the propagation of two Gaussian laser beams with $w_0 = 1.0$ and 0.5 mm, respectively, both beams have $\lambda = 0.633$ µm.

For a laser beam the Rayleigh range z_R is defined as that at $z = z_R$ the beam radius is $w(z_R) = \sqrt{2}w_0$. From Eq. 2.1 we can find that.

$$z_R = \frac{\pi w_0^2}{\lambda} \tag{2.4}$$

z_R is proportional to w_0^2. z_R for the two laser beams are marked out in Fig. 2.1. From Eq. 2.1 we can also find that at far field, z is large, term $\lambda z/\pi w_0^2 = z/z_R$ » 1, the $1/e^2$ intensity beam far field half divergent angle θ can be found by

$$\begin{aligned}\theta &= \frac{w(z)}{z} \\ &= \frac{\lambda}{\pi w_0} \\ &= \frac{w_0}{z_R}\end{aligned} \tag{2.5}$$

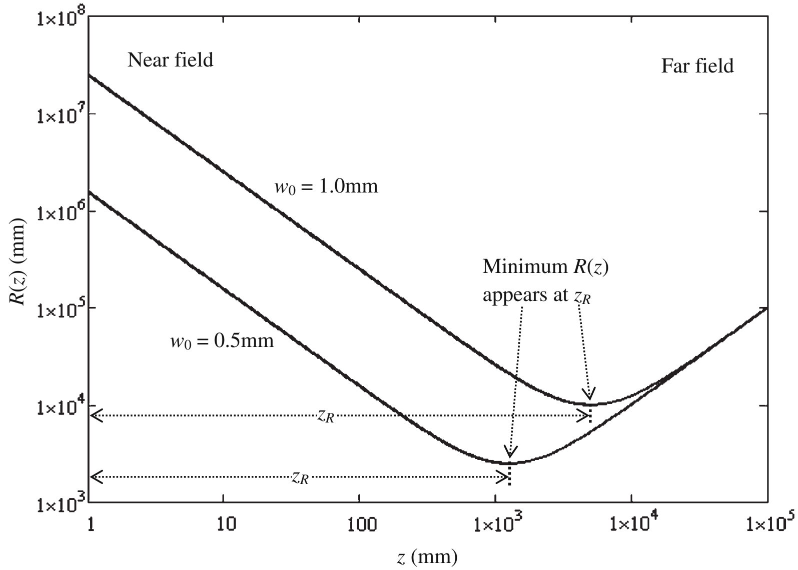

Fig. 2.2 *Thick curves* are $R(z)$ versus z for two laser beams with $w_0 = 1.0$ and 0.5 mm, respectively

θ is inversely proportional to the beam waist w_0. θ defines the asymptote line for a laser beam, as shown in Fig. 2.1.

Figure 2.2 plots Eq. 2.2 for two laser beams same as the two beams shown in Fig. 2.1. It can be seen from Eq. 2.2 and Fig. (2.2) that at the beam waist, both beams have a plane wavefront with radius $R(0)$ approaching infinity. As the beam propagates, $R(z)$ gradually decreases. The minimum wavefront radius appears at $z = z_R$. As the beam continues propagating, the beam wavefront gradually becomes spherical, then $R(z)$ becomes proportional to z. z_R is often used as a criterion, $z \ll z_R$ is "near field", $z \gg z_R$ is "far field", and $z \sim z_R$ is the intermediate field.

Figure 2.3 plots Eq. 2.3 for a laser beam with Gaussian intensity distribution in an arbitrary cross section perpendicular to the propagation direction of the beam, where $I_0(z)$ is normalized to 1. Beam radius is usually defined at either 1/e^2 intensity level or at FWHM level, as shown in Fig. 2.3. We can find from Eq. 2.3 that the 1/e^2 intensity radius equals to $w(z)$, and the half magnitude radius equals to 0.59 $w(z)$. The ratio between these two radii is about 1.7.

The percentage laser energy encircled inside the 1/e^2 intensity radius can be calculated by.

$$\frac{\int_0^{w(z)} e^{-2r^2/w(z)^2} r dr}{\int_0^{\infty} e^{-2r^2/w(z)^2} r dr} = 86.4\,\% \tag{2.6}$$

where r is the radial variable. Similarly, the percentage laser energy encircled inside the half magnitude radius can be calculated by

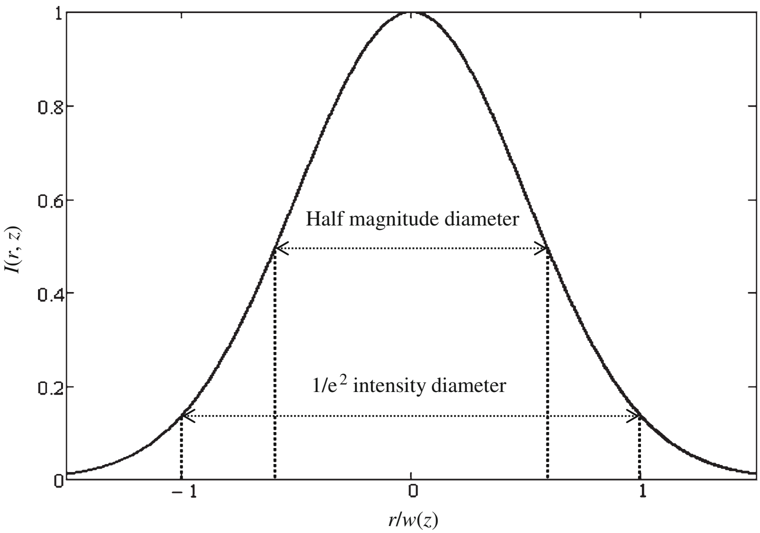

Fig. 2.3 Normalized gaussian intensity distribution

$$\frac{\int_0^{0.59w(z)} e^{-2r^2/w(z)^2} r dr}{\int_0^{\infty} e^{-2r^2/w(z)^2} r dr} = 69.2\,\% \tag{2.7}$$

The characteristics of basic transverse mode Gaussian beams have been studied in depth. Many literatures studying this subject have been published. The most cited one is the book written by Siegman [1].

2.2 M^2 Factor Approximation

The beams of some solid state lasers and laser diodes are not exact basic mode Gaussian beams, they may contain higher order Gaussian modes. It is difficult to find the mode structure details in these beams, since the unavoidable measurement errors often lead to inconclusive results. But all these non-basic Gaussian mode beams will have far field divergences larger than the far field divergences of basic mode Gaussian beams with the same beam waist radii. A practical way of handling such laser beams is to neglect the mode structure details, assume the beams still have Gaussian intensity distributions and introduce a "M^2 factor" to the beams. Eqs. 2.1 and 2.2 are modified to the forms [2]

$$w(z) = w_0 \left[1 + \left(\frac{M^2 \lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \tag{2.8}$$

$$R(z) = z\left[1 + \left(\frac{\pi w_0^2}{M^2 \lambda z}\right)^2\right] \tag{2.9}$$

The beam Rayleigh range and the far field divergence become, respectively

$$z_R = \frac{\pi w_0^2}{M^2 \lambda} \tag{2.10}$$

$$\begin{aligned} \theta &= \frac{w(z)}{z} \\ &= \frac{M^2 \lambda}{\pi w_0} \\ &= \frac{w_0}{z_R} \end{aligned} \tag{2.11}$$

By definition $M^2 \geq 1$. For $M^2 = 1$, Eqs. 2.8–2.11 reduce to Eqs. 2.1, 2.2, 2.4 and 2.5, the beam reduces to a basic mode Gaussian beam. Figures 2.4 and 2.5 plot Eqs. 2.8 and 2.9 for two beams with $M^2 = 1$ and 1.2, respectively, both beams have $w_0 = 1.0$ mm and $\lambda = 0.633$ mm. Most collimated single TE mode laser diode beams have a M^2 of $1.1 \sim 1.2$. M^2 factor has been widely used now to describe various quasi Gaussian laser beams. Some laser developers even use M^2 factor to describe multi TE mode laser beams. To this author's opinion, this is not an appropriate use of M^2 factor.

2.3 Collimation or Focusing a Laser Diode Beam: Thin lens Equation

Thin lens equation was originally derived as a simple analytical model to describe how a lens manipulates geometric rays.[1] Thin lens equation is an approximated model, but accurate enough in most applications, and is therefore widely used. With some modifications, thin lens equation can be used to describe how a laser beam propagates through a lens. In this book we use thin lens equation as the main mathematical model.

The widely used thin lens equation for geometric rays emitted by an object point has the form

$$\frac{i}{f} = \frac{o}{o - f} \tag{2.12}$$

[1] Almost any optics text book discusses thin lens equations and Snell's law.

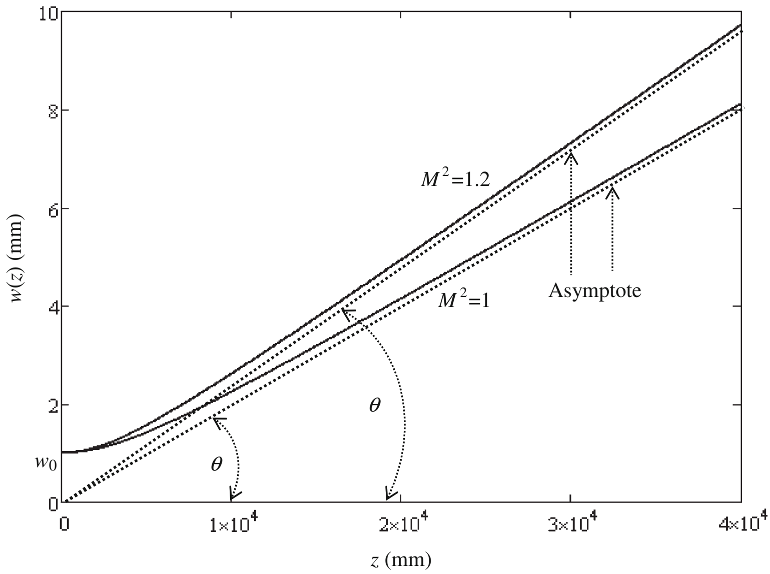

Fig. 2.4 *Thick curves* are $w(z)$ versus z for two laser beams with $w_0 = 1.0$ mm, and $M^2 = 1$ and 1.2, respectively

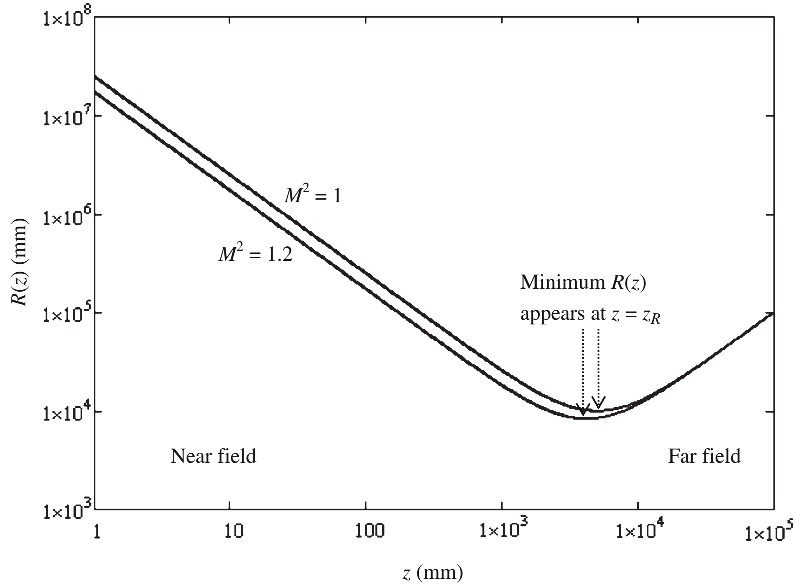

Fig. 2.5 *Thick curves* are $R(z)$ versus z for of two laser beams with $w_0 = 1.0$ mm, and $M^2 = 1$ and 1.2, respectively

where o is the object distance measured from the object point to the lens principal plane, the lens focuses the rays from the object point and produces an image of the object point, i is the image distance measured from the image point to the lens principal plane, and f is the focal length of the lens. The lens magnification ratio m is given by

$$m = \frac{i}{o} \tag{2.13}$$

Equation 2.12 shows that for $o = f_+$, $i \to \infty$ and $m \to \infty$, the rays are collimated, where f_+ means a value slightly larger than f. For $o = f_-$, $i \to -\infty$ and $m \to -\infty$, the rays are also collimated, where f_- means a value slightly smaller than f. For $o \to \infty$, $i \to f$ and $m \to 0$, the rays are focused. It's noted that the actual smallest possible focused spot radius is the diffraction limited radius $1.22\lambda f/d$, where λ is the light wavelength and d is the ray bundle diameter.

Equation 2.12 was first modified to be applicable to a basic mode Gaussian beam without considering the M^2 factor [3] and later expanded to include the M^2 factor [4]. The later form of thin lens equation looks like that

$$\frac{i}{f} = \frac{\frac{o}{f}\left(\frac{o}{f} - 1\right) + \left(\frac{z_R}{M^2 f}\right)^2}{\left(\frac{o}{f} - 1\right)^2 + \left(\frac{z_R}{M^2 f}\right)^2} \tag{2.14}$$

where o is the object distance measured from the waist of the laser beam incident on the lens to the principal plane of the lens, i is the image distance measured from the waist of the laser beam output from the lens to the principal plane of the lens, and z_R is the incoming laser beam Rayleigh range defined in Eq. 2.4 (if use the z_R defined in Eq. 2.10, the M^2 factor will be used twice). $z_R/(M^2 f)$ is an important parameter in Eq. 2.14. For $z_R/(M^2 f) \to 0$, Eq. 2.14 reduces to Eq. 2.12, that means such a laser beam can be considered as geometric rays emitted by an object point. For $z_R/(M^2 f) \to \infty$, Eq. 2.14 leads to $i = f$, the laser beam is focused. Section 2.4 will discuss the collimation and focusing of laser beams in more details.

Equation 2.14 has some interesting characteristics that are different from Eq. 2.13. One characteristics is the maximum and minimum focusing distance that can be found by differentiating Eq. 2.14 and let $\Delta i/\Delta o = 0$, we obtain

$$o = f \pm z_R/M^2 \tag{2.15}$$

Plug $o = f + z_R/M^2$ into Eq. 2.14 we can find the maximum focusing distance as.

$$i_{\max} = f\,\frac{\frac{2z_R}{M^2 f} + 1}{\frac{2z_R}{M^2 f}} \tag{2.16}$$

Plug $o = f - z_R/M^2$ into Eq. 2.14 we can find the minimum focusing distance as

$$i_{\min} = f\frac{\frac{2z_R}{M^2 f} - 1}{\frac{2z_R}{M^2 f}} \tag{2.17}$$

$z_R/(M^2f)$ again play an important role here. For $z_R/(M^2f) \gg 1$, Eqs. 2.16 and 2.17 lead to $i_{\max} = i_{\min} = f$, that is a focusing situation. For $z_R/(M^2f) \ll 1$, Eqs. 2.16 and 2.17 lead to $i_{\max} \to \infty$ and $i_{\min} \to -\infty$, the beam is collimated similar to collimated geometric rays emitted by an object point.

For a typical laser diode beam, z_R is several microns, assuming this laser diode beam is collimated by a lens with a focal length of several millimeters, we have $z_R/(M^2f) \sim 0.001$, Eq. 2.16 reduces to $i_{\max} \approx f^2M^2/2z_R \approx 500f \sim 1$ m, Eq. 2.17 reduces to $i_{\min} \approx -f^2M^2/2z_R \approx -500f \sim -1$ m, the negative value of $i_{\min}$ indicates that the laser beam outgoing from the lens has an imaginary waist at the left hand side of the collimation lens.

The waist of a collimated laser diode beam is a few millimeters, the z_R of the collimated beam is several meters. When this collimated laser diode beam is focused by a lens with a focal length of tens of millimeters, we have $z_R/(M^2f) \sim 100$, Eqs. 2.16 and 2.17 give $i_{\max} \approx 1.01f$ and $i_{\min} \approx 0.99f$, respectively, the focused spot of the beam can shift around the lens focal point in the range of ~ 10 μm.

Equation 2.14 is plotted in Fig. 2.6 by dash curves with $z_R/(M^2f)$ being a parameter, Eq. 2.12 is also plotted in Fig. 2.6 by the solid curve for comparison. Figure 2.6 shows that for $o/f = 1$, $i/f = 1$ for any $z_R/(M^2f)$ values. The maximum and minimum focusing distances $i_{\max}$ and $i_{\min}$ are marked by the black dots and squares on each curve. For smaller $z_R/(M^2f)$, i changes faster as o changes and the value of $i_{\max}$ and $|i_{\min}|$ are larger.

The magnification of a laser beam propagating through a lens is defined by the ratio of w_0'/w_0, where w_0' is the waist radius of the beam output from the lens. w_0'/w_0 can be found by modifying Eq. 2.13 as [4].

$$m = \frac{w_0'}{w_0} = \frac{1}{[(\frac{o}{f} - 1)^2 + (\frac{z_R}{M^2 f})^2]^{0.5}} \tag{2.18}$$

$w_0'/w_0 \gg 1$ indicates the beam is collimated. $w_0'/w_0 \ll 1$ indicates the beam is focused. $w_0'/w_0 = 1$ means the beam is relayed. From Eq. 2.18 we can see that $w_0'/w_0 = 1$ can appear for various combinations of o/f and $z_R/(M^2f)$. It can be seen that for $z_R/(M^2f) \to 0$, Eq. 2.18 reduces to Eq. 2.13.

Equation 2.18 is plotted in Fig. 2.7 with $z_R/(M^2f)$ as a parameter. We can see from Fig. 2.7 that for any $z_R/(M^2f)$ values, m peaks at $o/f = 1$. For $o/f = 1$, m is larger for smaller $z_R/(M^2f)$, since this is a collimation situation, the waist size of a collimated beam is much larger than the waist size of the incident beam. For $z_R/(M^2f) > 1$, the value of m does not change much as the value of o/f changes,

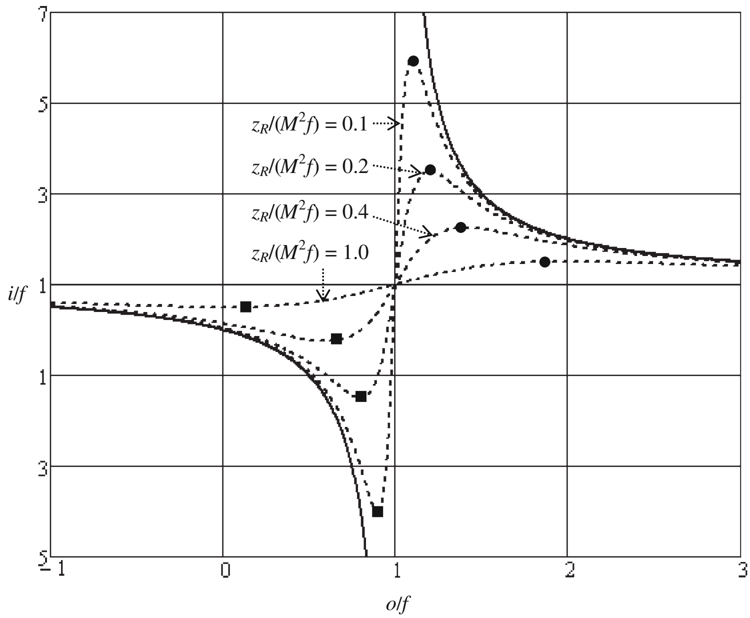

Fig. 2.6 *i*/*f* versus *o*/*f* curves. The *dash curves* are for several laser beams with $z_R/(M^2f)$ being a parameter. The *solid curves* are for geometric rays emitted by an object point for comparison. i_{max} and i_{min} are marked by *black dots* and *squares* on each curve, respectively

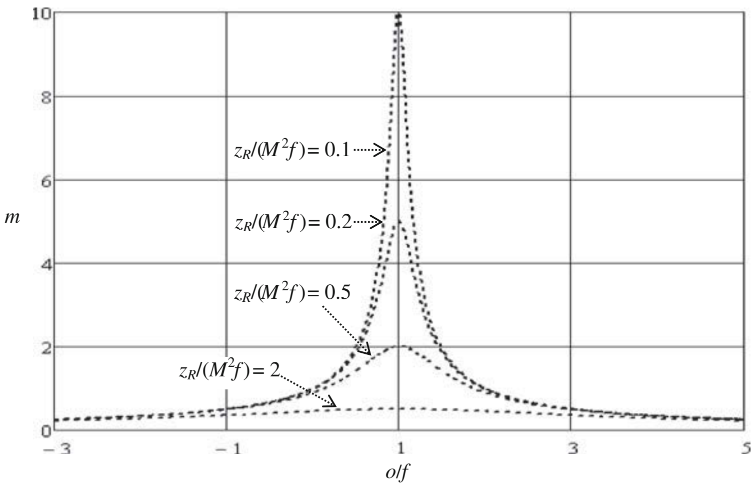

Fig. 2.7 *m* versus *o*/*f* curve with $z_R/(M^2f)$ as a parameter

since this is a focusing situation, the waist size of the focused beam or the focused spot does not change much.

(a)

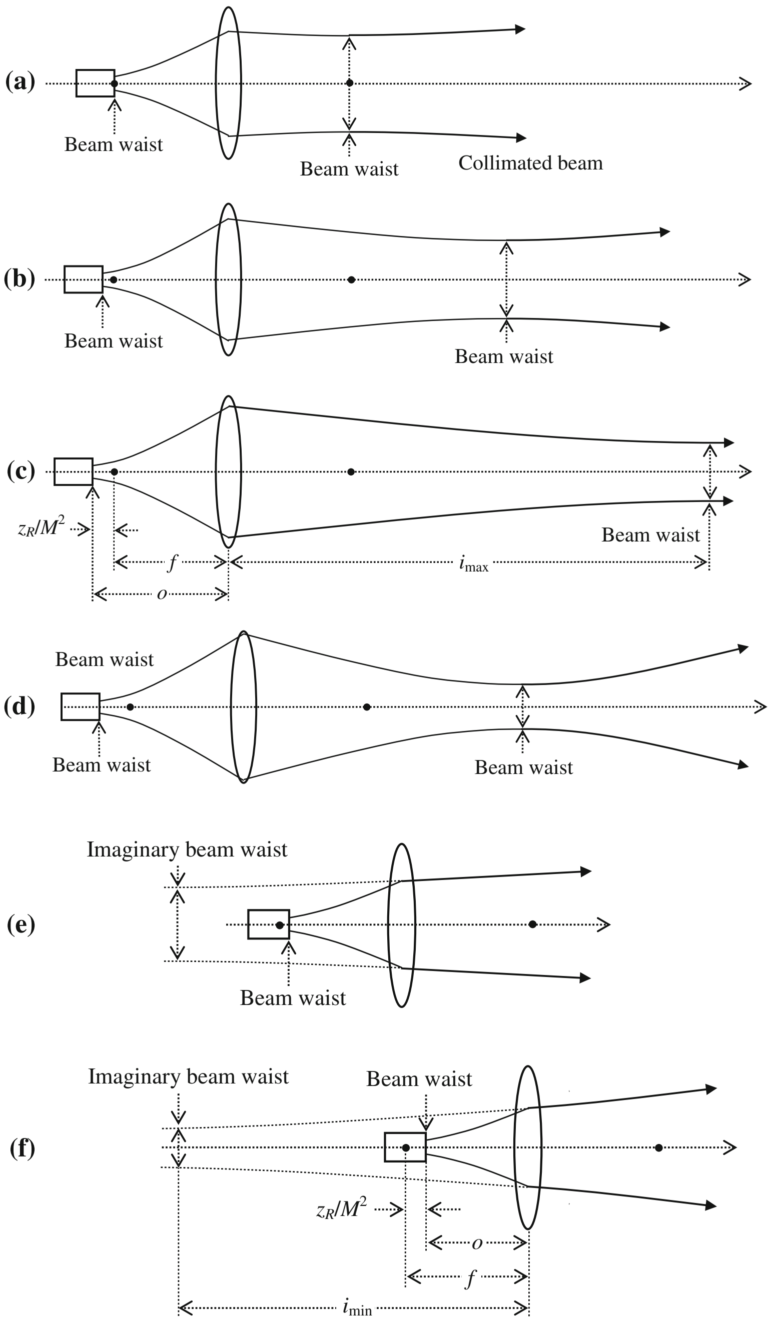

Fig. 2.8 Illustration of the collimating characteristics of a laser diode beam. The *black dots* denote the focal points of the lens

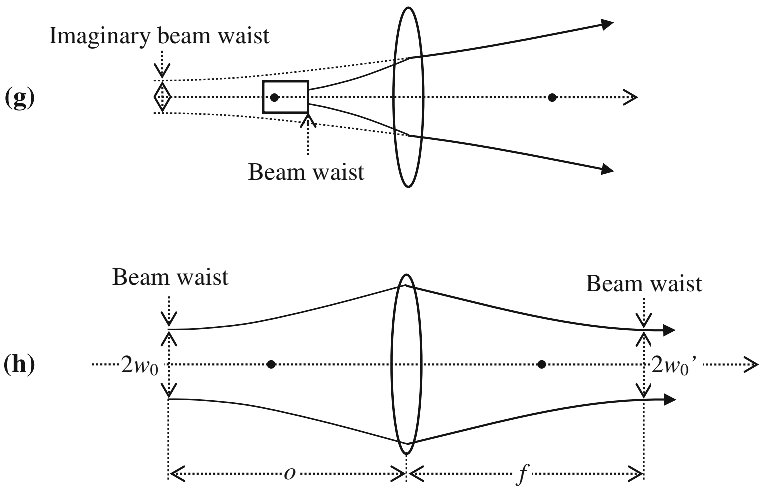

Fig. 2.8 continued

2.4 Collimation or Focusing a Laser Diode Beam: Graphical explanations

In Sect. 2.3, we discussed the mathematical model describing the collimation or focusing of a laser beam. In this section we draw several graphs to provide a more clear view about the collimating or focusing of a laser diode beam. We start from the collimating situation.

Figure 2.8a shows a laser beam with its waist located at the focal plane of the lens, the beam is collimated after propagating through the lens, the waist of the collimated beam is located at the other focal plane of the lens. Figure 2.8b shows the waist of the input laser beam moves away from the focal plane of the lens by a small distance, the waist of the beam propagated through the lens also moves away from the lens focal plane, this beam is not well collimated. Figure 2.8c shows the waist of the input laser beam moves away from the lens to a location with $o = f + z_R/M^2$, then the waist of the beam propagated through the lens reaches the maximum focusing distance $i_{\max}$. Figure 2.8d shows the waist of the input laser beam moves further away from the lens, the waist of the beam propagated through the lens starts moving back towards the lens. We note that the waist size of the beam output from the lens changes in Fig. 2.8a–d, and that the waist positions of the beam output from the lens are the same in Fig. 2.8b and d, but the waist sizes are different.

When the waist of the input laser beam moves from the collimated position shown in Fig. 2.8a towards the lens by a small distance, the beam propagated through the lens is still divergent with the imaginary beam waist appearing at the left hand side of the lens, as shown in Fig. 2.8e. Figure 2.8f shows the waist of the input laser beam moves closer to the lens to a location with $o = f - z_R/M^2$, then

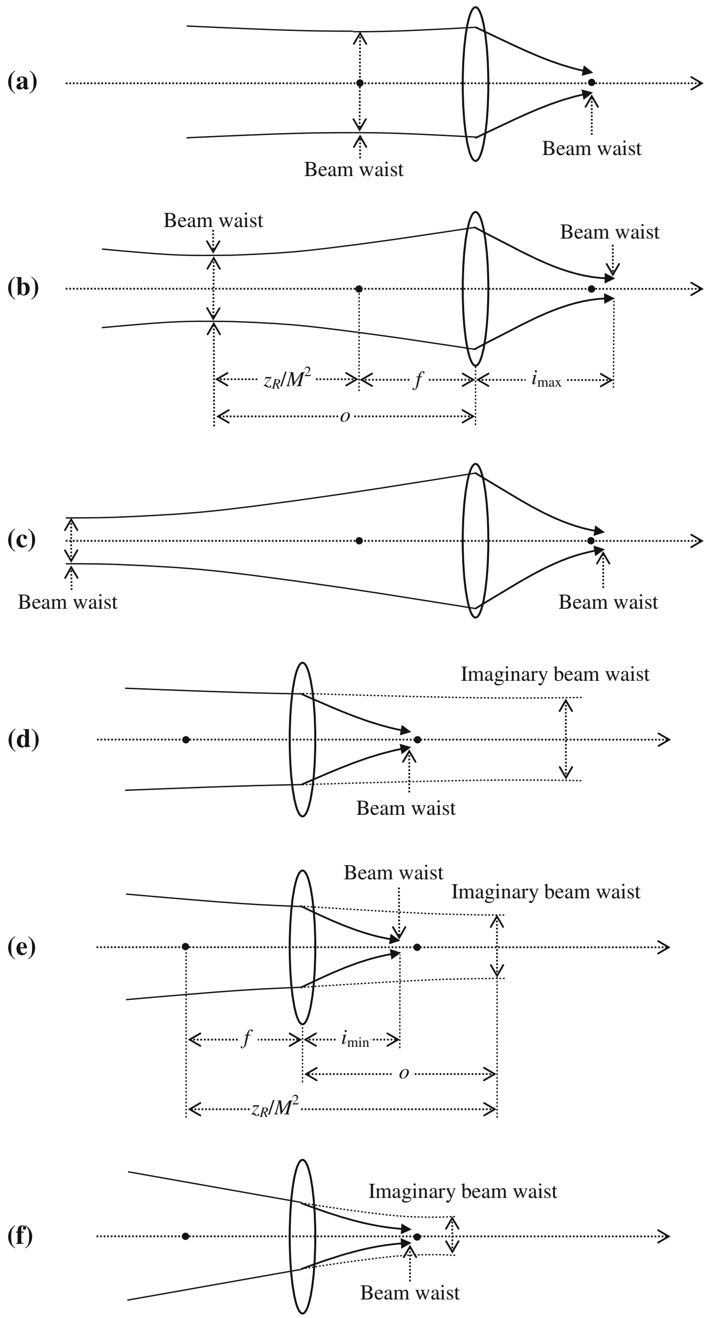

Fig. 2.9 Illustration of the focusing characteristics of a laser diode beam. The *black dots* denote the focal points of the lens

the imaginary waist of the beam propagated through the lens reaches the minimum focusing distance $i_{\min}$. Figure 2.8g shows the waist of the input laser beam moves further closer to the lens, the imaginary waist of the beam propagated through the lens starts moving back towards the lens. Figure 2.8h shows the laser diode beam waist is located at $(o/f - 1)^2 = 0.5$ with $z_R^2/(M^2 f)^2 = 0.5$. According to Eqs. 2.18 and 2.14, we have $i = o$ and $w_0^{'} = w_0$, respectively, the beam is relayed.

In Fig. 2.8a–h, the value of $z_R/M^2/f$ is visibly smaller than 1, the situation can be categorized as collimation situation. It's noted that the drawings in Fig. 2.8 are only for illustration purpose, they don't have the exact proportions.

The focusing characteristics of a laser diode beam is illustrated in Fig. 2.9. We start from the situation shown in Fig. 2.9a, where the waist of the input laser beam is located at the focal plane of the lens, the beam propagated through the lens is focused with its waist located at the other focal plane of the lens. Figure 2.9b shows the waist of the input laser beam moves away from the lens to a location with $o = f + z_R/M^2$, the waist of the beam propagated through the lens reaches the maximum focusing distance $i_{\max}$. Figure 2.9c shows the waist of the input laser beam moves further away from the lens, the waist of the beam propagated through the lens starts moving back towards the lens. Figure 2.9d shows the input laser beam with its imaginary waist at the right hand side of the lens as shown by the dot curves (that means if there is no lens, the laser beam waist will reach there), the waist of the beam propagated through the lens also moves away from the lens focal point towards the lens. Figure 2.9e shows the imaginary waist of the input laser beam moves toward the lens from the right hand side to a position with $o = f - z_R/M^2 = -(z_R/M^2 - f)$, the waist of the beam propagated through the lens reaches the minimum focusing distance $i_{\min}$, the negative sign of o indicates that the waist of the input laser beam is at the right hand side of the lens. Figure 2.9f shows the waist of the input laser beam moves further towards the lens, the waist of the beam propagated through the lens starts moving away from the lens back towards the lens focal point.

We note that in Fig. 2.9a–f, $z_R/(M^2 f) > 1$, the situation can be categorized as focusing situation. The drawings in Fig. 2.9 are only for illustration purpose, they don't have the exact proportions.

2.5 An Example of Collimating and Focusing a Laser Diode Beam

A numerical example can help to better understand the collimation and focusing characteristics of laser diode beams. We consider a laser diode beam with $1/e^2$ intensity beam waist radius of 0.5 and 1.5 μm in the fast and slow axis direction, respectively, and a wavelength of 0.67 μm. Here we assume $M^2 = 1$ and the beam astigmatism $A = 0$ for simplicity. This laser diode beam is collimated by a lens with a focal length of $f_1 = 10$ mm and then focused by another lens with a focal length $f_2 = 100$ mm, as shown in Fig. 2.10.

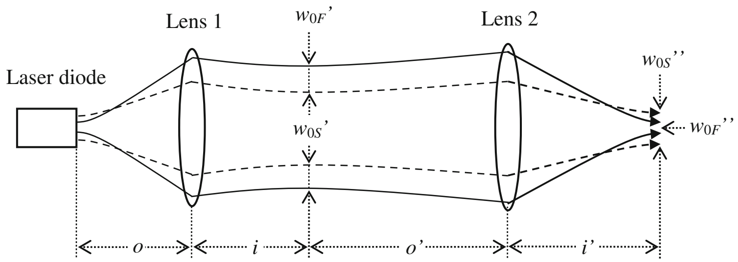

Fig. 2.10 A laser diode beam is collimated by a lens and focused by another lens. The *solid curves* and *dash curves* are for the beams in the fast and slow axis directions, respectively

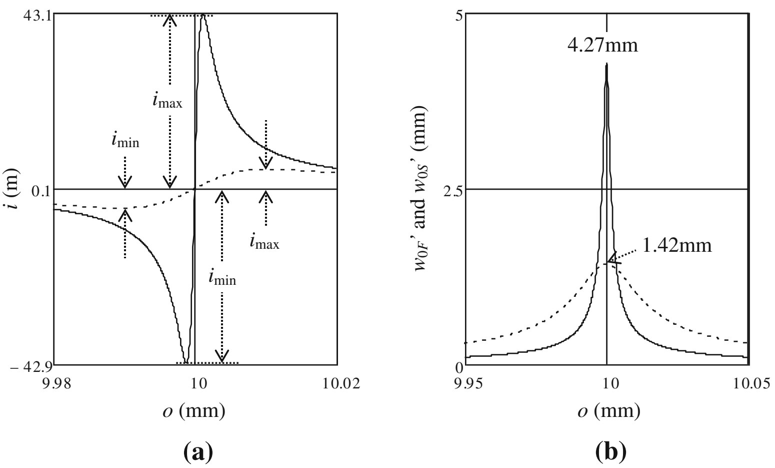

Fig. 2.11 A laser diode beam is collimated by a lens with 10 mm focal length. **a** i versus o curve. **b** w_{0F}'' and w_{0S}'' versus o curves. In both **a** and **b** the *solid* and *dash curves* are for the fast and slow axis directions, respectively

From Eq. 2.10 we find the Rayleigh ranges in the fast and slow axis directions for this laser diode beam to be $z_{RF} = 1.17$ µm and $z_{RS} = 10.55$ µm, respectively. The i versus o curve, and the w_{0F}' and w_{0S}' versus o curves described by Eqs. 2.14 and 2.18 for lens 1 are plotted in Fig. 2.11a and b, respectively, where w_{0F}' and w_{0S}' are the waist radius in the fast and slow axis direction, respectively, of the beam propagated through the lens. It's noted that the middle points at the horizontal and vertical axes in Fig. 2.11a and the middle point at the horizontal axis of Fig. 2.11b are the value of f_1. It can be seen that in the fast axis direction, the maximum focusing distance is about 43 m, in the slow axis direction the maximum focusing distance is about 4.7 m. In a collimation situation shown in Fig. 2.11a, w_{0F}' and w_{0S}' can be calculated by Eq. 2.18 to be $w_{0F}' = m \times 0.5$ µm ≈ 4.27 mm and $w_{0S}' =$

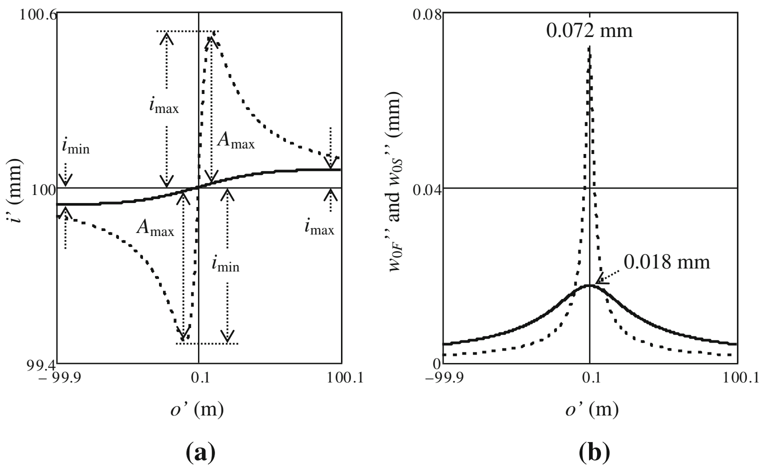

Fig. 2.12 A collimated laser diode beam is focused by a lens with 100 mm focal length. **a** i' versus o' curve. **b** w_{0F}'' and w_{0S}'' versus o' curves. In both **a** and **b** the *solid* and *dash curves* are for the fast and slow axis directions, respectively

$m \times 1.5$ μm $\approx$ 1.42 mm. When $o \neq f$, the beam is not well collimated, w_{0F}' and w_{0S}' are smaller than 4.27 and 1.42 mm, respectively, as shown in Fig. 2.11b.

After being collimated, the laser diode beam has larger waist radius and smaller divergence in the fast axis direction than in the slow axis. From Eq. 2.10 we can find the Rayleigh ranges for this collimated laser diode beam to be $z_{RF}' = 85.3$ m and $z_{RS}' = 9.5$ m in the fast and slow axis directions, respectively. The collimated laser diode beam is then focused by lens 2 with a focal length of $f_2 = 100$ mm. The i' versus o' curve, and the w_{0F}'' and w_{0S}'' versus o' curves are plotted in Fig. 2.12a and b, respectively, where w_{0F}'' and w_{0S}'' are the waist radius of the focused beam in the fast and slow axis direction, respectively. As we can see in Fig. 2.12a that the maximum and minimum focusing distances in the slow axis direction is about 100.53 and 99.47 mm, respectively. The maximum and minimum focusing distances in the fast axis direction is about 100.06 and 99.94 mm, respectively. The waist radius of the beam focused by lens 2 can be calculated using Eq. 2.18 as $w_{0F}'' = m \times 4.27$ mm ≈ 0.018 mm and $w_{0S}'' = m \times 1.42$ mm ≈ 0.072 mm. It's noted that the middle points at the horizontal and vertical axes in Fig. 2.12a and the middle point at the horizontal axis of Fig. 2.12b are the value of f_2.

From Fig. 2.12a we can see one interesting phenomenon; if $o' \neq f_2$, the waists of the focused beam in the fast and slow axis can appear at different positions, although the laser diode considered in this case has no astigmatism. We call this phenomenon "ghost astigmatism". For the setup shown in Fig. 2.10, the maximum ghost astigmatism A_{max} is about 0.52 mm that appears at $o' = f_2 + z_{RS}' = 9.6$ m, as shown in Fig. 2.12a. From Fig. 2.12b we can see another interesting phenomenon;

when $o' = f_2$, the beam is best focused with the focused spot sizes being the largest in both fast and slow axis directions. The best focused beam has the largest focused spot, that sounds weird, but it is the characteristics of Gaussian laser beams. So, if we want a smallest possible focused spot, we can defocus the beam. For example, when the beam in the slow axis direction is focused at the maximum focusing distance with $o' = f_2 + z_{RS}' = 9.6$ m, the focused spot radius is 0.018 mm, that is four times smaller than $w_{0S}'' = 0.072$ mm.

2.6 Raytracing Technique

Thin lens equation is an approximation that is only appropriate to simulate the propagation of a laser beam through a thin lens. In some applications, more accurate step by step raytracing is required.

When a ray propagates through an air/glass interface, the ray will be refracted according to Snell law[2]

$$n \sin\theta = n' \sin\theta' \tag{2.19}$$

where n and n' are the air and glass refractive indices, respectively, θ and θ' are the ray incident and exit angles with respect to the local normal of the lens surface, respectively. In a design case, the laser beam parameters, the lens surface profile, and the distance between the laser beam waist and the lens surface vertex are known, we can determine the position of the point on the lens surface where the $1/e^2$ intensity contour of the incident laser beam contacts the lens surface, as shown in Fig. 2.13, that means z, $w(z)$ and $R(z)$ can be found. A conceived incident ray perpendicularly passing through the wavefront at this contacting point can be determined, as shown in Fig. 2.13. Applying Snell law to this ray, we can determine a conceived ray refracted by the lens surface. The conceived refracted ray has an angle θ''between it and the local normal of the lens surface, as shown in Fig. 2.13. Since the equation describes this local normal can be found using the lens surface profile, θ can be found too and θ' can be calculated by Eq. 2.19. The angle ϕ between the conceived refracted ray and the optical axis can be found. Then we can find the radius of the wavefront perpendicular to the refracted ray by

$$R'(z) = \frac{w'(z)}{\tan\phi} \tag{2.20}$$

where $w'(z) = w(z)$ is the refracted beam size at this point, as shown in Fig. 2.13. Now we find $w'(z)$ and $R'(z)$, we can calculate the waist radius w'_0 of the refracted beam and the distance z' along the optical axis from the contacting point to the waist of the refracted beam by modifying Eqs. 2.1 and 2.2 to

[2] Almost any optics text books discusses Snell law

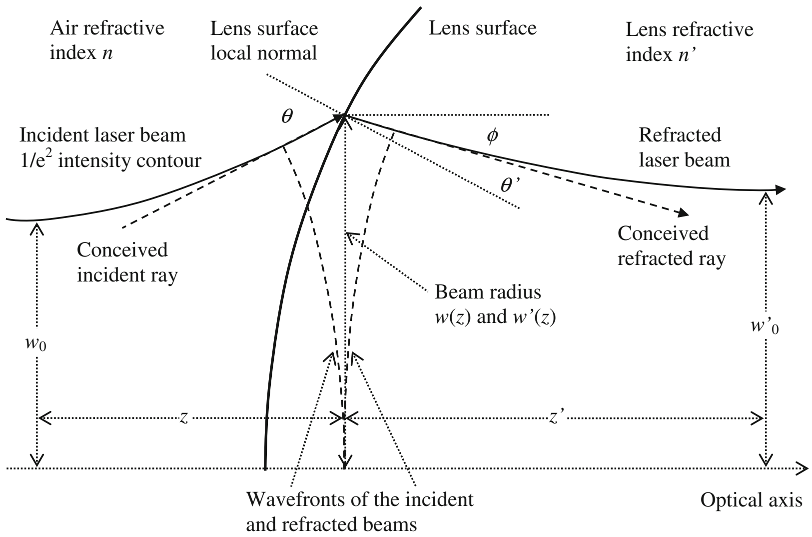

Fig. 2.13 A lens surface refracts a laser beam

$$w_0' = \frac{w'(z)\pi^{0.5}}{[1 + \frac{w'(z)^4\pi^2}{R'(z)^2(M^2\lambda)^2}]^{0.5}} \tag{2.21}$$

$$z' = \frac{R'(z)}{1 + \frac{R'(z)^2(M^2\lambda)^2}{w'(z)^4\pi^2}} \tag{2.22}$$

This raytracing technique is more time consuming, but provides accurate results.

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Chapter 3
Single Transverse Laser Diode Beam Manipulation Optics

Abstract Various types of optics for manipulating single TE mode laser diode beams are discussed with emphasis on optics for delivering small beam spots to a certain distance, circularizing elliptical beams, correcting beam astigmatism, and single mode fiber coupling. We have discussed single TE mode laser diode beam basics in previous chapters. In this chapter we will discuss the more practical optics for manipulating single TE laser diode beams.

Keywords Single TE mode · Circularizing · Astigmatism · Fiber coupling · Beam shape · Aperture · Spot size

3.1 Collimating and Focusing

3.1.1 Lenses

Single TE mode laser diode beams have large divergent angles. If use conventional spherical lenses to collimate or focus such beams, a group of lenses must be used to minimize the spherical aberrations, the weight and size of such a lens group will be larger than single element aspheric lens. Therefore, single element aspheric lenses are more often used to collimate and focus laser diode beams. Tens of different aspheric lenses specially designed and fabricated for laser diode beam collimation are available in the market. Although these special aspheric lenses are expensive, usually cost tens of dollars a lens, they will eventually save the user time, cost and space, and offer high collimated beam quality. Once a laser diode beam is collimated, it's no longer highly divergent and is much easier to handle, conventional spherical lenses can be used to further manipulate the collimated beams.

H. Sun, *Laser Diode Beam Basics, Manipulations and Characterizations*,
SpringerBriefs in Physics, DOI: 10.1007/978-94-007-4664-0_3,

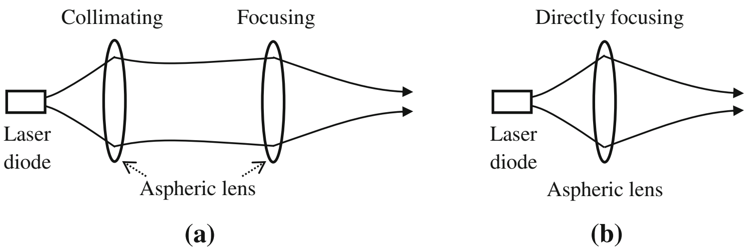


Fig. 3.1 **a** Using the first aspheric lens to collimate and second aspheric lenses to focus a laser diode beam. **b** Directly focusing a laser diode beam using one aspheric lens

There are few aspheric lenses specially designed and fabricated for directly focusing a laser diode beam. Using an aspheric lens designed for collimating use to focus a laser diode beam will cause severe aberration, the focused spot will be much larger than it should be and with a lot diffractions. The most common way of focusing a laser diode beam is to use two collimating lenses, the first lens is to collimate the beam, the second lens is to focus the collimated beam, as shown in Fig. 3.1. Thereby both lenses are used in their best conditions and the focused beam has the least aberrations. By properly choosing the focal length ratio of the two lenses used, we can obtain the desired magnification ratio or focused spot size.

Most aspheric lenses available in market for collimating laser diode beams have a numerical aperture below 0.6, these lenses will more or less clip the beam in the fast axis direction and cause side lobes, focusing rings and focal shift, etc. In most applications, the beam clipping effects are acceptable. Further increasing the numerical aperture of a lens requires the use of an expensive multi elements lens group, such lens groups are rarely seen. The effects of aperture clipping on a beam will be discussed in Sect. 3.6 “Aperture clipping effects”.

3.1.2 Beam Shape Evolution

The waist of a single TE laser diode beam is elliptical with the major axis of the ellipse in the slow axis direction as shown in Fig. 3.2a. The beam diverts faster in the fast axis direction than in the slow axis direction, since the beam divergence is inversely proportional to its waist size. As the beam propagates, the beam shape becomes circular at certain distance, as shown in Fig. 3.2b. This certain distance depends on the beam waist size and wavelength, and is usually several microns. Beyond this distance, the beam continues diverting fast in the fast axis direction, the beam shape gradually transforms to elliptical again with the major axis in the fast axis direction, as shown in Fig. 3.2c.

If the beam of a single TE mode laser diode is collimated, the major axis of the waist of the collimated beam is in the fast axis direction, as shown in Fig. 3.2d. Then the divergence of the collimated beam is smaller in the fast axis direction

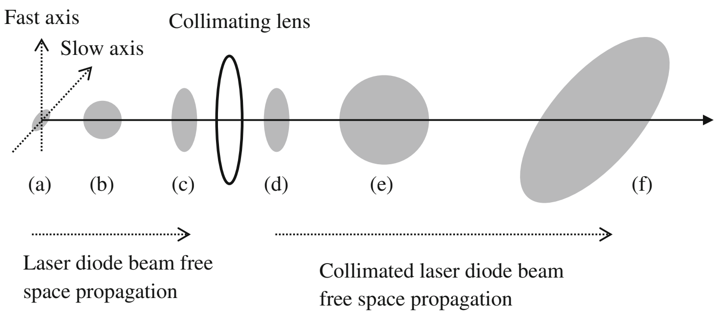


Fig. 3.2 Shape of a single TE mode laser diode beam evolves as the beam propagates in free space and through a collimating lens

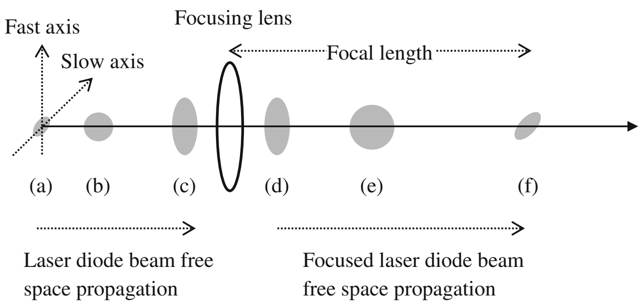


Fig. 3.3 Shape of a laser diode beam evolves as the beam propagates in free space and through a focusing lens

than in the slow axis direction. As the collimated beam propagates, the beam shape becomes circular at certain distance, as shown in Fig. 3.2e. This certain distance depends on the collimated beam waist size and the wavelength, and is usually in the range of meters. Beyond this certain distance, the beam shape will become elliptical again with the major axis in the slow axis direction, as shown in Fig. 3.2f.

If the beam of a single TE mode laser diode is focused, the focused spot is the image of the beam waist. The major axis of the focused spot is in the slow axis direction, as shown in Fig. 3.3f. At somewhere in between the focusing lens and the focused spot, the beam shape is circular, as shown in Fig. 3.3e.

3.1.3 Collimated or Focused Beam Quality Check

Both the lens quality and the alignment accuracy of the laser diode beam to the lens will affect the quality of a collimated or focused beam. The quality of a

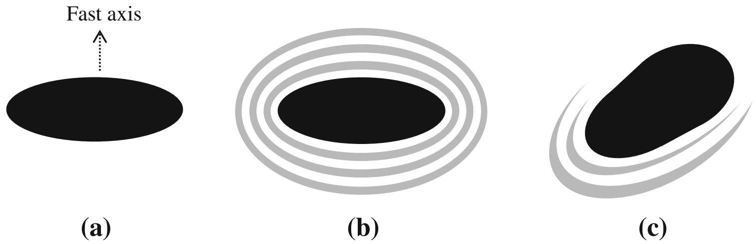


Fig. 3.4 Three far field spot patterns of collimated laser diode beams

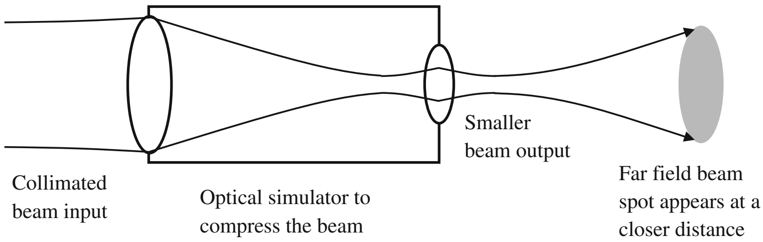


Fig. 3.5 Schematic of an optical simulator

collimated single TE mode laser diode beam can be checked by visually observing the far field beam pattern tens of meters away. If a laser diode beam is well aligned to a high quality aspheric lens with a large numerical aperture of 0.5 or up, the collimated beam should have a clean symmetric spot with no diffraction rings and little scattering as shown in Fig. 3.4a. If the laser diode beam is well aligned with a high quality aspheric lens with small numerical aperture of 0.3 or lower, there will be diffraction rings mainly in the fast axis direction, because the lens clips the beam in the fast axis direction. Figure 3.4b shows a symmetric beam spot with several diffraction rings around it, such a spot pattern indicates that the laser diode is not well positioned longitudinal to the lens, but well positioned transversely. Figure 3.4c shows an asymmetric spot with asymmetric diffraction rings around it, such a spot pattern indicates that the laser diode beam waist is either not positioned on the optical axis of the lens or has a pointing error, or both.

The quality of a focused spot of a single TE mode laser diode beam can be checked at the focal plane of the focusing lens using the same criterion shown in Fig. 3.4, because the focal plane is optically at the far field.

Some lower price aspheric lenses have less smooth lens surface and will create visually noticeable scattering around the beam spot. However, the quality of a collimated or focused beam can be checked the same way.

An optical simulator can be used to bring the far field of a collimated beam to one meter or even closer. The simulator is a beam compressor or beam expander used in a reversed way, as shown in Fig. 3.5. As we can see from Eq. 2.10 that the

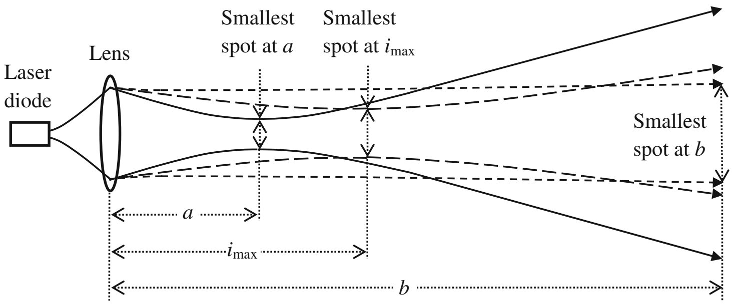


Fig. 3.6 One collimated beam and two focused beams. At different distances, these three beams offer different smallest spot

Rayleigh range of a beam is proportional to the square of the beam waist radius, the compressed beam will have a much smaller beam waist, a much shorter Rayleigh range and a much shorter far field distance.

3.2 Deliver a Smallest Beam Spot

Laser diode users often want to deliver a laser beam to a certain distance with a smallest possible spot for highest power density and want to know how small the spot can be. They often use the term "to collimate the beam" or "to focus the beam at this distance" to describe such a requirement. In some cases one of the two terms is correct. In some other cases, neither a collimated beam nor a focused beam can deliver the smallest possible spot to a certain distance. Figure 3.6 shows three examples, where the solid curve is for a beam focused at a short distance a, the long dash curve is for a beam focused at the maximum focusing distance i_{max}, and the short dash curve is for a collimated beam. For a long delivery distance, usually beyond tens of meters, a collimated beam can provide the smallest spot, as shown in Fig. 3.6 by distance b. The spot size or waist size of a collimated beam at certain distance can be found by first using Eq. 2.18 to calculate the waist radius of the collimated beam, assuming the waist radius of the laser diode beam is known, then using Eq. 2.8 to calculate the spot size at this certain distance. For a short delivery distance within the maximum focusing distance, a beam focused at that distance can offer the smallest spot, as shown by distance a. The spot size can be found by first using Eq. 2.14 to calculate the object distance o needed to focus the beam at a, then using Eq. 2.18 to calculate the spot size at a, assuming the waist radius of the laser diode beam is known. For a delivery distance of i_{max}, the beam focused at i_{max} will offer the smallest spot size as shown in Fig. 3.6.

If the beam delivery distance is beyond the maximum focusing distance i_{max}, but not very long, the situation is more complicated and can be analyzed in the following way. For a given value of o, the corresponding i and w_o' can be

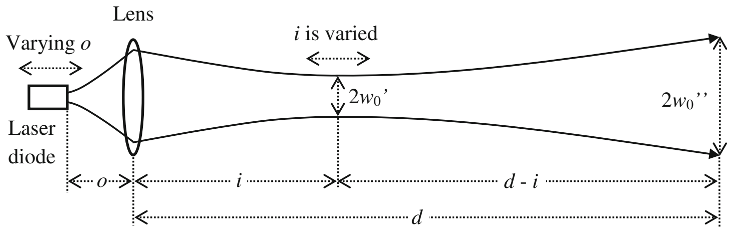


Fig. 3.7 Moving the laser diode along the optical axis to find the smallest spot size $2w_o^{'}$ of the beam at a certain delivery distance d

calculated using Eqs. 2.14 and 2.18. The spot size $w_o^{''}$ at the beam delivery distance d can be calculated using Eq. 3.1

$$w_0'' = w_0'\{1 + [\frac{M^2\lambda(d-i)}{\pi w_0'^2}]^2\}^{0.5} \tag{3.1}$$

Equation 3.1 is modified from Eq. 2.8 by replacing z by $d - i$, as explained in Fig. 3.7. The smallest spot size at the delivery distance d can be found by varying o around $o = f$, where f is the focal length of the lens, and monitoring the spot size change at the delivery distance d, till the smallest spot is found. Although this process takes some time to complete, the result is very simple and is explained below.

Let $o = f$, the beam is collimated. The collimated beam waist radius can be calculated, we can find the far field divergent angle for this collimated beam using Eq. 2.11 and draw an asymptote line for this collimated beam. The radius of the smallest spot at any delivery distance is given by this asymptote line with the beam being either collimated or focused, as shown in Fig. 3.8. Utilizing the result shown in Fig. 3.8, we can find the smallest spot size at any beam delivery distance much faster. A detailed analysis of this subject can be found in [1].

3.3 Line Generator

Laser light lines are used in many construction and medical alignment applications. Laser diode is often the choice of the laser to generate such a laser line. The simplest way of generate a laser line is to collimate the beam first, then use a cylindrical lens or a glass rod to divert the laser beam in one direction, as shown in Fig. 3.9. The laser line fan angle ϕ as well as the line length b is proportional to the collimated beam size a, as shown in Fig. 3.9. The elliptical shape beams of laser diodes offers easy adjustment of line length by rotating the beam about its optical axis. Laser line generators are usually specified by fan angle.

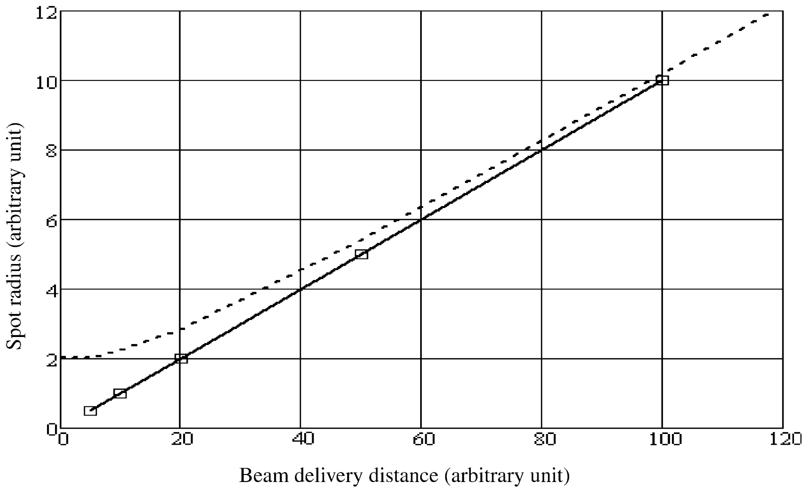
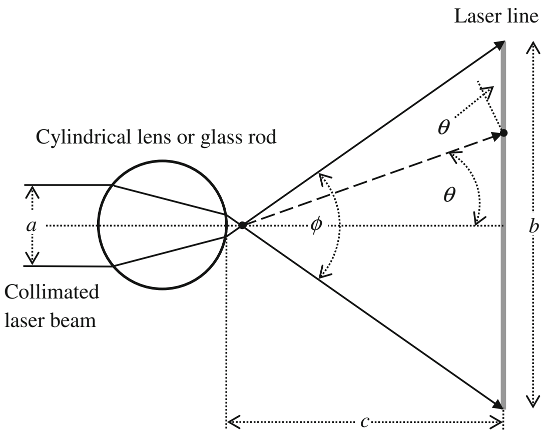


Fig. 3.8 The *dash curve* is the radius of a collimated laser diode beam as a function of propagation distance. The *solid line* is the asymptote of the *dash curve*. The smallest spot radius is given by the solid line for any beam delivery distance

Fig. 3.9 Generate a laser line with fan angle ϕ using a cylindrical lens or a glass rod



Applications using laser lines are illumination types, not imaging types. The light intensity distribution along the line is the main concern. Consider a point on the laser line marked by the black dot and a working distance c, as shown in Fig. 3.9. The distance from the focal point to the point considered is $\approx c/\cos(\theta)$, since c is usually much larger than the lens focal length. θ is the angle this point imposes on the focal point. This distance factor contains term of $\cos(\theta)^{-1}$ and reduces the intensity of this ray by a factor of $\cos(\theta)$ compared with the ray hitting the center of the laser line. When the ray hits the considered point, the ray is projected onto the laser line with angle $\cos(\theta)$, the intensity of the ray is reduced

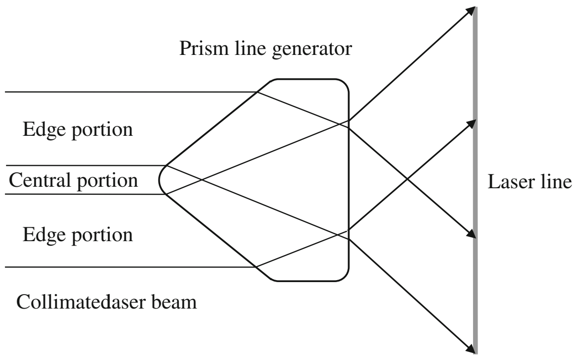


Fig. 3.10 A special prism generates a laser line with more uniform intensity distribution

by another factor of $\cos(\theta)$. Therefore, the laser line has an intensity reduction factor of $\cos(\theta)^2$ imposed on the quasi Gaussian intensity distribution of the collimated laser diode beam. This $\cos(\theta)^2$ factor makes the intensity profile of a laser line have narrower central peak and longer tails, particularly for large fan angle laser line, where θ can be as large as 60° at the edge of the laser line.

In order to generate a laser line with more uniform intensity distribution, a special prism was developed as shown in Fig. 3.10. When a collimated laser diode beam propagates through the prism, the central portion of the beam is transformed to a laser line by the cylindrical part of the prism, as shown in Fig. 3.10. Since a laser diode beam has quasi Gaussian intensity distribution, the central portion of the beam has relatively flat intensity distribution, the laser line formed by the central portion of the beam also has relatively flat intensity distribution. Furthermore, the two edge portions of the beam are deflected by the flat parts of the prism and projected onto the two edges of the laser line, as shown in Fig. 3.10, this will increase the intensity level of the two edge portions of the laser line. Therefore, the laser line generated by such a prism has an intensity distribution much more uniform with shorter tails compared with a Gaussian profile.

This prism can be found in Edmund Optics catalog.

3.4 Beam Circularization and Astigmatism Correction

In some applications, a circular shape laser diode beam is more desirable than an elliptical shape beam. Circularizing laser diode elliptical beams becomes a special technical issue. On the other hand, an astigmatism free laser diode beam is sometimes beneficial. Since some widely used techniques can both circularize an elliptical beam and correct the astigmatism, we discuss these two issues in the same section.

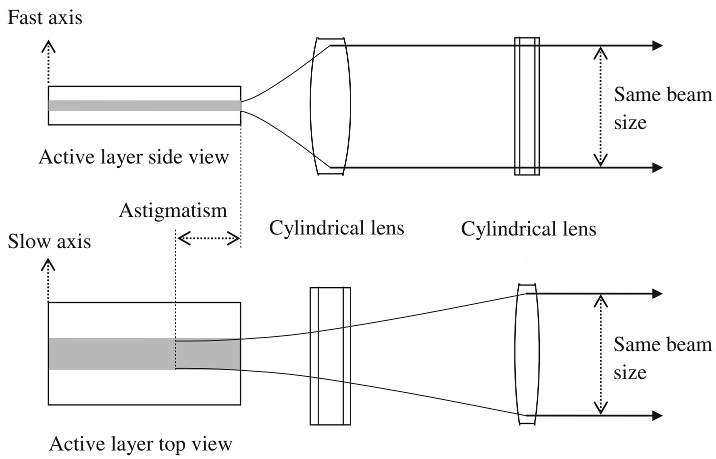


Fig. 3.11 Using two orthogonal positioned cylindrical lenses to collimate and circularize an elliptical laser diode beam as well as to correct the astigmatism of the beam

3.4.1 Using Two Cylindrical Lenses to Collimate and Circularize an Elliptical Beam and to Correct the Astigmatism

When thinking about collimating, circularizing and correcting astigmatism for a laser diode beam, the first idea usually coming up is to use a pair of orthogonally positioned cylindrical lenses. As shown in Fig. 3.11, a cylindrical lens with higher power is placed a few millimeters away from the laser diode to collimate the laser diode beam in the fast axis direction, another cylindrical lens with lower power is placed about 10 mm away from the laser diode to collimate the beam in the slow axis directions. The focal lengths of the two cylindrical lenses are so chosen that after collimation, the beam sizes in the fast and slow axis directions are the same, as shown in Fig. 3.11. Then the beam is collimated, the elliptical beam shape is circularized, and the astigmatic is corrected.

Although the idea shown in Fig. 3.11 sounds great, it has big problems in reality. First, the large divergent angle of the beam in the fast axis direction requires the cylindrical lens to be aspheric. Aspheric cylindrical lenses are difficult to fabricate, rarely seen and expensive. Second, the higher power cylindrical lens will be thick, and introduce aberration in the slow axis direction into the beam. This effect combined with the not very small divergence of the beam in the slow axis direction also requires the lower power cylindrical lens to be aspheric. Therefore, in reality only multi TE mode laser diode beams are collimated by a pair of spherical cylindrical lenses, because these high power multi TE modes beams are often used for illumination types of applications, where aberration is not a concern.

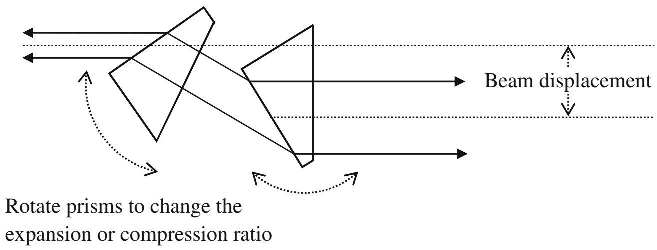


Fig. 3.12 A pair of anamorphic prisms can expand or compress the beam in one direction. Propagating from *left* to *right*, the beam is expanded. Propagating from *right* to *left*, the beam is compressed. The expansion or compression ration can be adjusted by rotating the prisms

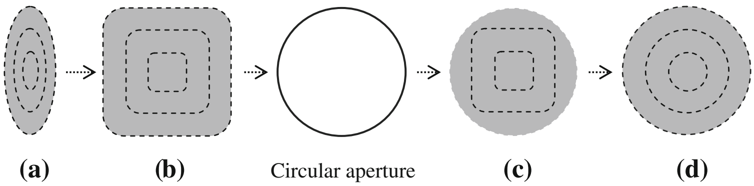


Fig. 3.13 The shape and intensity contour of a collimated laser diode beam change as the beam propagates through a pair of anamorphic prisms and a circular aperture. The *grey shapes* describe the beam shapes, the *dash curves* describe the intensity contours

3.4.2 Using Anamorphic Prism Pair and a Circular Aperture to Circularize the Beam

As shown in Fig. 3.12, a pair of anamorphic prisms can either expand or compress a laser diode beam in one direction. A collimated elliptical beam of a laser diode can be circularized by either expand the beam in the minor axis direction or compress the beam in the major axis direction. The expansion or compression ratio can be adjusted from about 2 to 6 by rotating the prisms. After propagating through the prism pair, the beam will have several millimeters transverse displacement as shown in Fig. 3.12. We can see from Fig. 3.12 that one prism can also expand or compress the beam, only with less expansion or compression ratio and the beam propagation direction will be changed. After being expanded or compressed by an anamorphic prisms pairs, the beam needs be clipped by a circular aperture. During the circularizing process, the beam intensity profile will be going through the following changes, as shown in Fig. 3.13:

(a) A collimated laser diode beam is elliptical with elliptical intensity contours.
(b) After being expanded or compressed by a pair of anamorphic prisms, the beam and its intensity contours are square like with round corners.

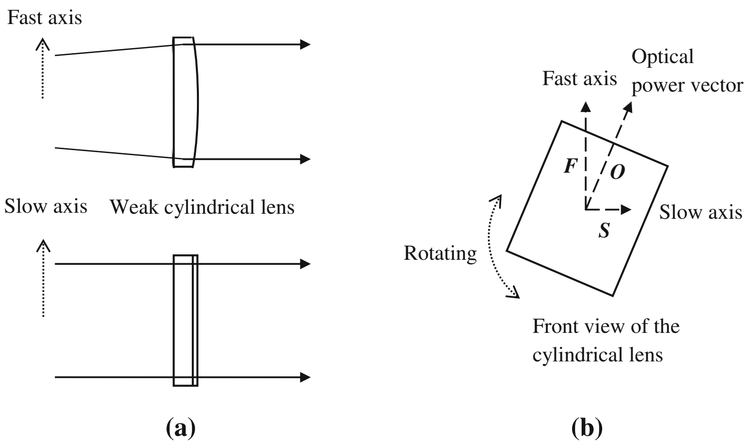


Fig. 3.14 Using a weak cylindrical lens to correct the astigmatism

(c) After being clipped by a circular aperture and within a short distance to the aperture, the beam has circular shape. However its intensity contours remain square like with round corners.
(d) After being clipped by a circular aperture and propagating a long distance, the beam evolves to a circular with circular intensity contours.

Using a circular aperture to clip the beam after the beam propagating through the anamorphic prism pair is a necessary step to circularize the beam, the clipping causes power lose and generates diffractions.

3.4.3 Using a Weak Cylindrical Lens to Correct the Astigmatism

After being collimated by an aspheric lens and circularized by a pair of anamorphic prisms, the astigmatism still in the beam can be corrected by a weak cylindrical lens with a few meters focal length. A positive cylindrical lens is usually used as shown in Fig. 3.14a, although a negative cylindrical lens can also be used by principle.

Different types of laser diodes have different astigmatism magnitudes. For a given laser diode, after being collimated by different lenses, the astigmatism in the beam is different. The chance is low to have a weak cylindrical lens with focal length just right to correct the astigmatism. The way of solving this problem is explained in Fig. 3.14b. The optical power of a cylindrical lens can be represented by a vector $\boldsymbol{O}$, that can be decomposed to two vectors $\boldsymbol{F}$ and $\boldsymbol{S}$ in the fast and slow axis directions, respectively, as shown in Fig. 3.14b. The net power of the cylindrical lens for correcting the astigmatism is given by $|\boldsymbol{F}| - |\boldsymbol{S}|$. Rotating the cylindrical lens about the beam axis, the magnitude of $|\boldsymbol{F}| - |\boldsymbol{S}|$ can be continuously

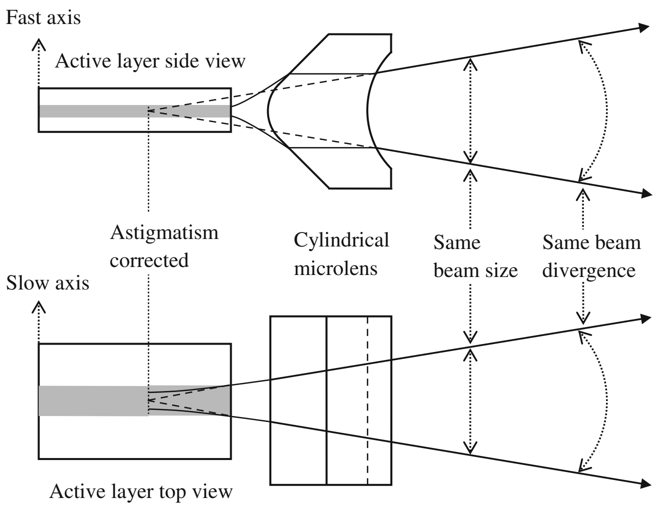


Fig. 3.15 Using a special cylindrical micro lens to circularize the beam and correct the astigmatism

varied from $-|\boldsymbol{O}|$ to $|\boldsymbol{O}|$. Using a cylindrical lens with a $|\boldsymbol{O}|$ more than needed, we can always find an angle at which the cylindrical lens makes the right correction of the astigmatism. Since the cylindrical lens is very weak, it's difficult to visually evaluate how well the astigmatism is corrected. Some type of wavefront sensing equipment should be used to measure the quality of the final beam.

3.4.4 Using a Special Cylindrical Micro Lens to Circularize an Elliptical Beam and to Correct the Astigmatism

A patented cylindrical micro lens was invented to circularize the elliptical beams of laser diodes and to correct the astigmatism. The micro lens has a diameter of about 100 μm and is placed tens of microns away from the laser diode in the slow axis direction, as shown in Fig. 3.15. When using the micro lens to manipulate the beam, the first surface of the lens collimates the beam in the fast axis direction, the second surface of the lens diverts the beam in the fast axis direction. When the prescription of the two surfaces, the thickness and the position of the micro lens are correct, the beam can be circularized and astigmatism free, as shown in Fig. 3.15.

As we mentioned in previous section, laser diodes of different types have different beam divergence and astigmatism. Even different laser diodes of the same type can have different beam divergence and astigmatism. Several slightly different micro lenses are available for choosing from, the lens position and

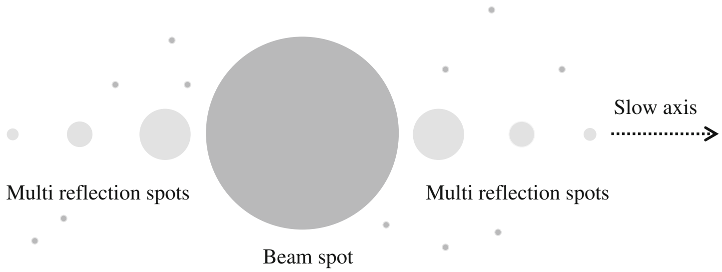


Fig. 3.16 The beam of Circulaser™ is visually not clean with multiple reflection spots and scattering. However, the beam quality is still good

orientation need be carefully adjusted and the beam need be real time monitored by a wavefront sensor. The final beam has a circularity of 1.2:1 or less.

Since the micro lens needs be positioned close to the laser diode, any tiny defects on the lens will be magnified and generate scattering. The beam will also be multiple reflected between the two surfaces of the lens because the small size of the lens. The final beam will look like that shown in Fig. 3.16, it's visually "dirty". Since human eye response to light intensity is nonlinear, the multiple reflection spots and scattering noticeable to human eyes are actually very weak and can be neglected. The quality of the circularized beam in terms of wavefront error is still good, usually with a peak to valley error of $<\lambda/4$. The micro lens is AR coated, but will still cause about 20 % power loss to the beam. This micro lens is not for retail sale in the market, it's licensed to Coherent Inc. and Blue Sky Research Inc. to be installed in their laser diode modules called Circulaser™.

3.4.5 *Using Single Mode Optic Fiber to Circularize an Elliptical Beam and to Correct the Astigmatism*

Another way of circularizing the elliptical beam of a laser diode and correct the astigmatism is to couple the beam into a single mode optic fiber. The beam inside the single mode optic fiber will be transformed to the TE mode of the fiber. Since the fiber is circular, the beam output from the fiber is circular and astigmatism free. To the author's experience, the beam output from a single mode fiber has the highest optical quality compared with the beams of Circulaser™ or the beam circularized by anamorphic prism pairs. The beam output from a single mode fiber is clean and pretty circular with a wavefront error of about $\lambda/10$.

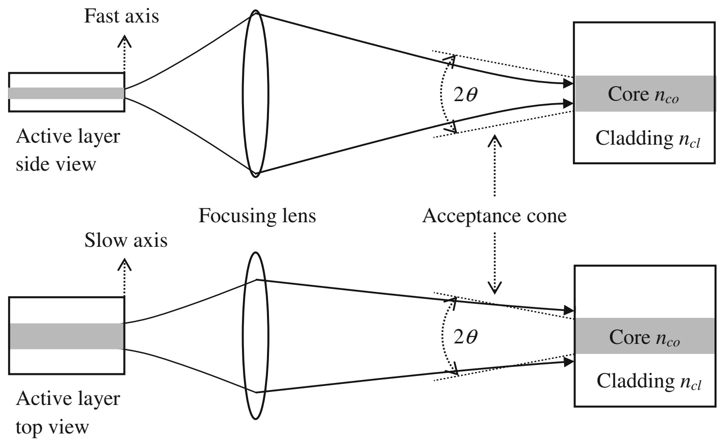


Fig. 3.17 Illustration of coupling a single TE mode laser diode beam into a single mode fiber, where θ is the acceptance cone angle of the fiber. When the beam in the fast axis direction is matched to the fiber core and acceptance cone, the focused spot size of the beam in the slow axis direction will be larger than the fiber core

3.5 Single Mode Optic Fiber Beam Delivery

Single mode optic fiber can well circularize the elliptical beam of laser diodes, correct the astigmatism, and deliver the beam to a location where a laser diode beam cannot directly reach, and therefore is widely used. Various laser diode modules with single mode fiber output are available in market, often with a nickname of "pigtail" modules. However, the coupling of a laser diode beam into a single mode fiber is not very easy.

Single mode fiber has a very small core size, it's about 6 µm for red color, and about 12 µm for 1.55 µm light. The light field inside a fiber is also called "mode". The fiber core size and the difference between the indexes of the fiber core and cladding determine the mode size. The output beam of a single mode fiber is very close to a Gaussian beam with the beam waist at the fiber output facet. The beam far field divergence is inversely proportional to the beam waist size and is about 10° or so FWHM. Single mode fiber core also has an acceptance cone given by [2]

$$\theta = \sin^{-1}[(n_{co}^2 - n_{cl}^2)^{0.5}] \tag{3.2}$$

where n_{co} and n_{cl} are the refractive indexes of the fiber core and cladding, respectively, as shown in Fig. 3.17. The acceptance cone is often expressed as numerical aperture (NA) with NA = $\sin\theta$. Most single mode optic fiber has an acceptance NA in the range of 0.1–0.15. Some special optic fiber can have acceptance the NA from 0.05 to 0.4.

To couple a single TE mode laser beam into a single mode optic fiber without big power loss, a laser diode beam must be focused to a spot smaller than the fiber

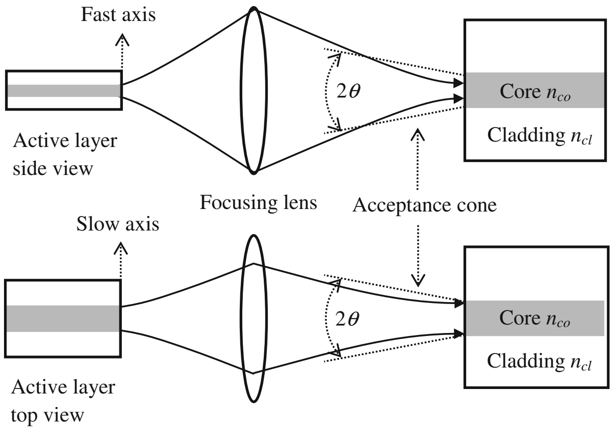


Fig. 3.18 Illustration of coupling a single TE mode laser diode beam into a single mode fiber, where θ is the acceptance cone angle of the fiber. When the beam in the slow axis direction is matched to the fiber core and acceptance cone, the convergent cone of the beam in the fast axis direction will be larger than the fiber acceptance cone

core size, and at the same time the beam convergent cone must be smaller than the fiber acceptance cone. Unfortunately, most single TE mode laser diode beams cannot meet these two requirements simultaneously. When a beam is focused in the fast axis direction to match the core size and acceptance cone of the fiber, the beam in the slow axis direction will have a focused spot larger than the core, as shown Fig. 3.17. When a beam is focused in the slow axis direction to match the core size and acceptance cone of the optic fiber, the beam in the fast axis direction will have a convergent cone angle larger than the fiber acceptance cone, as shown Fig. 3.18. This phenomenon is a result of the elliptical beam.

To couple a single TE mode laser diode beam into a single mode fiber without big power loss, the beam must also be well aligned to the fiber core. This involves three linear and two angular adjustments. The three linear adjustments are more critical than two angular adjustments. The two transversal adjustments are more critical than the longitudinal adjustment. A high quality *x–y–z* translation stage is required for the alignment, and some patience and experience are required as well. The practical coupling efficiency is about 50 %. The beam from a Circulaser™ is circular and can be coupled into a single mode fiber with efficiency up to about 80 %. However the Circulaser™ has about 20 % power loss caused by the micro lens to start with. As a comparison, gas laser beams are circular and can be focused to simultaneously match the core and acceptance cone of a single mode fiber, the coupling efficiency can be over 90 %.

It's noted that the divergent angle of a beam output from a single mode fiber is different from the acceptance cone angle of the fiber, since the cone angle given by Eq. 3.2 does not depend on the fiber mode size, while the divergent angle of the beam output from the fiber is inversely proportional to the mode size.

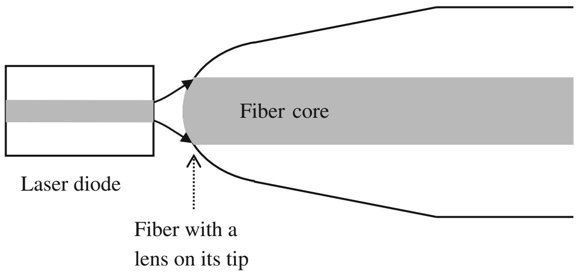


Fig. 3.19 A butt-end single mode optic fiber with a lens on its tip for directly coupling the beam of a single TE mode laser diode into the fiber

The tip of a single mode fiber can be chemically treated to form a lens, as shown in Fig. 3.19, such a fiber is called butt-end fiber. The fiber tip lens can focus the divergent beam of a laser diode and couple the beam directly into the fiber. The fiber must be placed within a few microns to the laser diode facet, since the beam has a large divergence. Butt-end fiber is not easy to find in market.

3.6 Aperture Beam Clipping Effects

Single TE mode laser diode beams have divergences in the fast axis direction larger than the numerical apertures of most collimating lenses, therefore the beam will most likely be clipped by lens edges, and the effects of clipping on beams should be aware of. There is no analytical mathematical model that can treat all the clipping cases. Numerical calculation using diffraction theory is not simple. In this book, we qualitatively discuss beam clipping effects.

Figure 3.20 is a schematic of a collimating lens clips a laser diode beam. The clipping usually takes place at the front surface of the lens since the beam there has large divergent angle. The second surface of the lens could further clip the beam. A clipping on the beam will have four major effects: reduce the beam waist size, shift the beam waist position or focal shift, change the beam intensity profile, and increase the M^2 factor of the beam.

Shortly after the beam is clipped, the beam $1/e^2$ intensity size will be smaller than the lens clear aperture, as shown in Fig. 3.20. When the clipping level is low, say at $1/e^2$ level, the $1/e^2$ intensity size of the clipped beam will be several percent smaller than the lens clear aperture. When the clipping level is high, say at 50 % level, the $1/e^2$ intensity size of the clipped beam will be a few percent smaller than the lens clear aperture. The clipping will introduce diffraction into the beam and make the beam more divergent as shown in Fig. 3.20. For a focused beam, the clipping on the beam will shift the focused spot towards the lens. When the clipping level is < 50 %, a focal shift of < 1 % of the focal length would be a fair estimation.

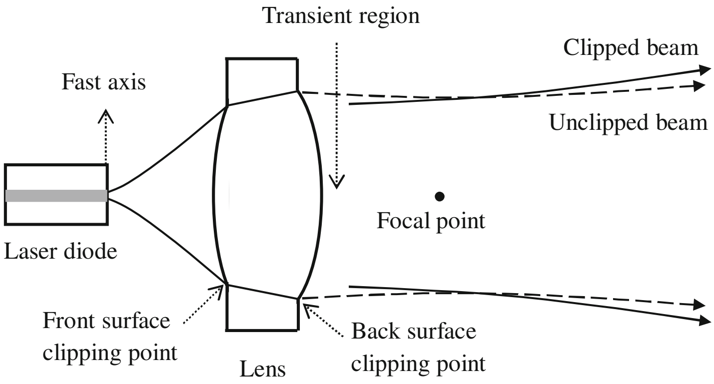


Fig. 3.20 Schematic of a collimating lens clipping a laser diode beam in the fast axis direction. The *dash curve* is for unclipped beam, the *solid curve* is for clipped beam

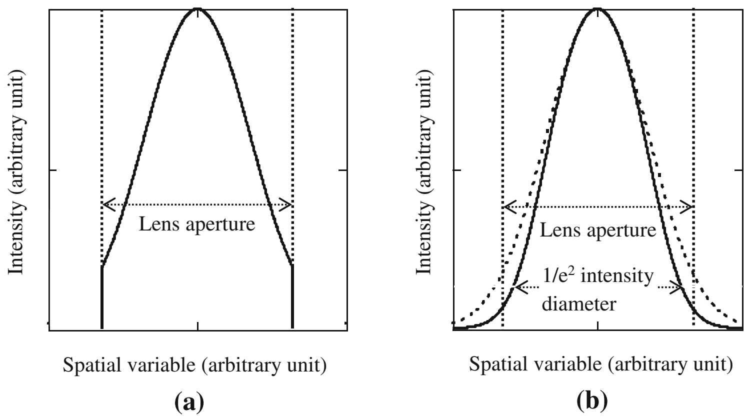
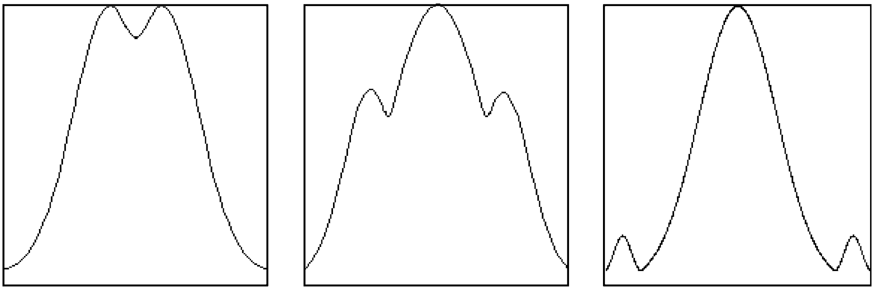


Fig. 3.21 **a** Intensity profile of a beam immediately after being clipped. **b** Solid curve is the intensity profile of a beam a couple of millimeters away after being clipped, the profile is near Gaussian with longer tails and the $1/e^2$ intensity diameter being smaller than the lens aperture. *Dash curve* is the Gaussian intensity profile of the beam before being clipped for comparison

After being clipped, the intensity profile of the beam will go through a transient region of a few millimeter length, as shown in Fig. 3.20. Within this region, the beam intensity profile changes fast, Fig. 3.21 shows two typical intensity profiles. As the beam continuously propagates, the beam intensity profile keeps on changing, but the change is gradually slow down. Side lobes or sometimes twin peaks will appear. Side lobes and twin peaks are diffraction rings with different magnitudes and positions. Figure 3.22 shows three typical intensity profiles of a clipped laser diode beam several millimeters away and beyond from the clipping point. The magnitude of side lobes and the dip at the center of the twin peaks vary as the beam propagates, and can be up to 10 % or more in a real measurement,



(a) (b) (c)

Fig. 3.22 Three typical beam intensity profiles caused by aperture clipping several millimeters and beyond away from the clipping point. The *horizontal axis* is spatial variable with arbitrary units. The *vertical axis* is intensity with arbitrary unit

where all the effects of lens imperfection and misalignment are taken into account. Side lobes and twin peaks can appear and disappear in turn as the beam propagates or appear at the same distance. For a collimated beam, the diffraction effect will eventually take over at the far field, the side lobes and twin peaks will disappear, and the beam intensity profile will eventually change to a quasi Gaussian profile.

For a focused beam, side lobes and twin peaks can appear in the focused spot. By slightly defocusing the beam, we can likely get rid of the twin peaks at certain distance. However, side lobes are likely always there. Using an aperture to block the side lobe will create new side lobes, because side lobes are the result of diffraction, the additional aperture will diffract the beam too. Unless the additional aperture is placed within a couple of millimeter to the detector. In such a short distance, the diffraction fringes are not separated from the main beam spot, as shown in Fig. 3.21.

Clipping a laser diode beam will increase the beam far field divergence; that is a result of diffraction. The increment of divergence is more than the beam waist size reduction by clipping can account for, that means the beam M^2 factor is also increased. Collimated laser diode beams usually have a M^2 factor from 1.1 to 1.2.

3.7 Diffractive Optics

Various diffractive optical elements have been developed to generate various beam patterns, to focus the beam like a conventional lens, or to shape a beam. Figure 3.23 shows several beam patterns often seen. Diffractive optics can generate much more patterns than those shown in Fig. 3.23. Diffractive optics has a micro structure in it and utilizes diffractions to perform the designed tasks. Diffraction effects take certain distance to work. If two diffractive optics are placed in a raw, the second diffractive optics will likely interfere the performance of the first diffractive optics, and the beam will be a mess, such a setup should be avoided.

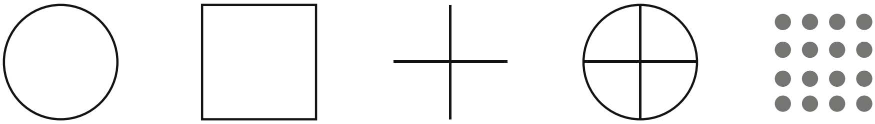


Fig. 3.23 Some commonly seen beam patterns generated by diffractive optics

Diffractive optics can work only for certain wavelength, incident angle and usually for a collimated beam. They are rarely used in a complex optical path with many conventional lenses in it.

3.8 Beam Shaping

For single TE mode laser diode, beam shaping often means transform a Gaussian beam to a flat-top or top-hat beam, because many applications require a flat-top beam. Figure 3.24a shows a two lens beam shaper, where the ray density represents the beam intensity. The input beam has dense rays in the central region, the ray density gradually drops towards the edge of the beam. The first lens is aspheric concave that has more power in its central region. After propagating through the first lens, the rays in the beam central region are more divergent than the rays at the beam edge. The second lens is aspheric convex, has more power its central region. After propagating through the second lens, the beam is collimated with uniform ray density or a flat top intensity profile. Figure 3.24b shows a designed intensity profile of a flat-top beam shaper. For a real shaped beam, there are a lot noises and ripples in the flat part. Different types of beam shapers can have different types of intensity profiles too. Any beam shaper has a limited working range, usually a few meters. Beyond this range, the beam intensity profile will gradually change to a quasi Gaussian profile because of diffraction.

3.9 Effects of External Optical Feedback on Laser Diodes

The emitted laser power of a laser diode can be accidently or intentionally fed back into the laser diode active layer. A feedback of as low as 1 % of the emitted power can make the laser diode operation unstable. A higher level feedback can significantly increase the laser output power and possibly blow out the laser diode.

Figure 3.25 shows two examples of accidentally external feedback. In Fig. 3.25a a laser diode beam is focused onto an optical surface, such as a CD surface, with the waist of the focused beam on the surface. Since the beam has no divergence at its waist and the beam is incident on the surface in the normal

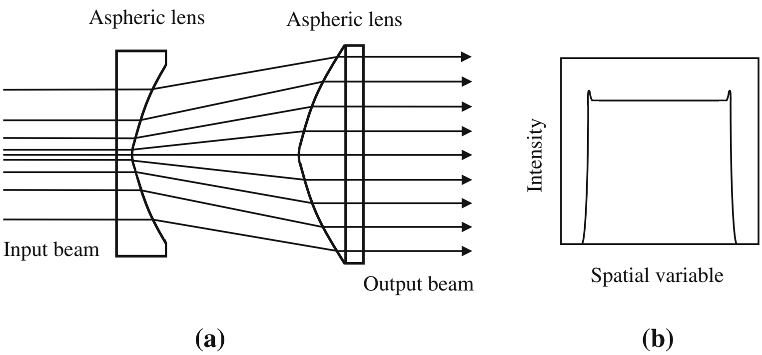


Fig. 3.24 **a** Two aspheric lenses forms a flat-top beam shaper. **b** An intensity profile of a flat-top beam shaper

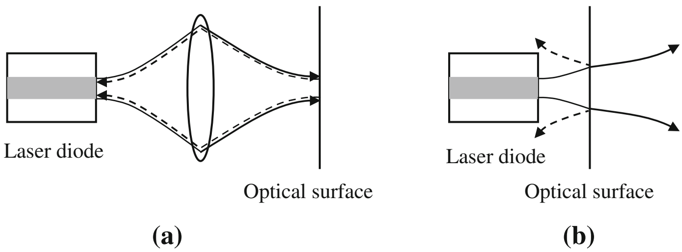


Fig. 3.25 **a** *Solid curves* are a single TE mode laser diode beam focused on an optical surface. *Dash curves* are the beam reflected by the optical surface back into the active layer. **b** *Solid curves* are a single TE mode laser diode beam incident on an optical surface positioned close to the laser diode. *Dash curves* are the beam reflected back by the optical surface

direction, the reflected beam will trace the incident path back into the active layer of the laser diode. If the feedback is unwanted, the optical surface should be tilted by a few degrees to deflect the reflected beam. Figure 3.25b shows an optical surface being positioned very close to the laser diode output facet. Although the beam reflected by the optical surface has large divergence, a certain portion of the laser power can still be fed back into the active layer. Since in such a situation the beam size is not much larger than the active layer size, the feedback level can be significant. If an optical surface must be placed within tens of microns distance to a laser diode, some type of laser power monitoring and controlling mechanism should be used to protect the laser diode from possible over driven.

Figure 3.26 shows an example of intentional external optical feedback, a fiber grating external cavity laser diode system. The laser diode has one facet HR coated and one facet AR coated, as shown in Fig. 3.26. A butt-end fiber with a refractive grating build in its core is positioned near the laser diode. The fiber grating will reflect portion of the laser power back into the active layer of the laser diode and output another portion of the laser power. The fiber grating and the HR coated

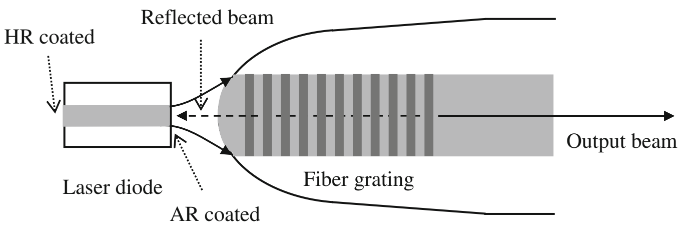


Fig. 3.26 Schematic of a fiber grating external cavity laser diode system

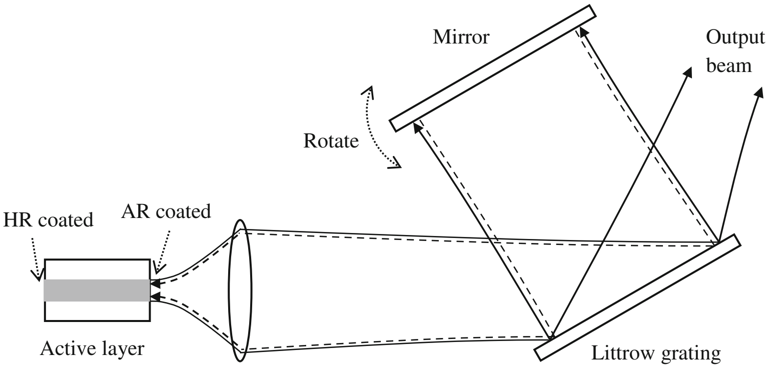


Fig. 3.27 Schematic of a grating external cavity laser diode system

facet of the laser diode forms a lasing cavity. The grating has a narrow spectral bandwidth, only the lasing wavelength inside the bandwidth will be reflected, and the laser diode is forced to operate at this wavelength with a very narrower linewidth.

Figure 3.27 shows another example of intentional external optical feedback, a grating external feedback wavelength tunable laser diode system. The laser diode also has its two facets HR and AR coated, respectively. The beam emitted from the laser diode is first collimated by a lens, and then incident on a Littrow grating. The zero order diffraction or the reflected beam of the grating is the output beam, as shown in Fig. 3.27. The first order diffraction beam of the grating is incident on a mirror. The mirror reflects the first order diffraction beam back to the laser diode active layer via the grating and the lens. The mirror and the HR coated facet of the laser diode forms the lasing cavity. Because of the dispersion function of the grating, the propagation direction of the first order diffraction is a function of laser wavelength. The mirror at certain angle will only reflect certain wavelength and force the laser to operate at this wavelength. The lasing wavelength can be tuned by tuning the mirror angle. The tuning range is limited by the active medium bandwidth. For 1.55 μm laser diode, the tuning range can be over 100 nm.

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Chapter 4
Multi Transverse Mode Laser Diode Beam Manipulation Optics

Abstract The method of calculating the spot size of a collimated or focused beam of multi TE mode laser diodes is discussed. Fiber delivery and micro prism shaping of multi TE mode laser diode beams are briefly described. Multi TE mode laser diode beams are of high power and mainly used in illumination type of applications where less accurate beam manipulation is required. Yet, multi TE mode laser diode beams have unique characteristics of both a Gaussian beam and a geometric beam, the collimation and focusing of multi TE mode laser diode beams should be analyzed differently.

Keywords Multi TE mode · Wide stripe · Laser stack · Collimating · Focusing · Spot size · Beam shaping · Beam delivery

4.1 Collimating and Focusing

To increase the laser power, the active layer width has to be increased. Such laser diodes are wide stripe laser diodes. The beams of wide stripe laser diodes contain multi TE modes as shown in Fig. 1.3. Each mode is a quasi Gaussian beam. To avoid confusion, we call the combination of all the TE modes "beam". The characteristics of the beam is more important to us than the characteristics of individual mode. In the fast axis direction, a beam of multi TE mode laser diode behaves the same way as a beam of single TE mode laser diode, we already know how to calculate the collimated or focused spot size at certain distance. While in the slow axis direction or along the wide stripe, the combination of many modes makes the beam behaves more like a geometric line light source. When analyzing the collimation or focusing of a multi TE mode laser diode beam, both geometric optics and Gaussian optics need be used.

H. Sun, *Laser Diode Beam Basics, Manipulations and Characterizations*, SpringerBriefs in Physics, DOI: 10.1007/978-94-007-4664-0_4,

4.1.1 Collimating a Wide Stripe Laser Diode Beam

Figure 4.1 shows a schematic of collimating a wide stripe multi TE mode laser diode beam, where a is the half size of the wide stripe and w_0 is the radius of the laser mode waist in the slow axis direction or in the wide strip direction, s is the overall spot size at working distance d. The often asked question regarding manipulating the beam of such a laser diode is how small the overall spot will be at a certain working distance when the beam is collimated? In this section, we discuss this issue.

When the beam is collimated by a lens, the wide strip and the mode are placed at the focal plane of the lens, a imposes an angle Ω to the optical axis of the lens, as shown in Fig. 4.1. At a working plane with distance d away, the half size of the image of the wide stripe is given by

$$\begin{aligned} a' &= d\Omega \\ &= d(a/f) \end{aligned} \tag{4.1}$$

where f is the lens focal length. The value of w_0 is usually a couple of microns and part of the mode leaks to the outside of the wide strip. So, it is a good approximation to assume the mode at the edge of the wide stripe is centered at the edge, as shown in Fig. 4.1. From a practically point of view, we are unlikely to find the exact location of edge mode in the wide stripe, we have to make such an approximation. This edge mode first propagates in the direction parallel to the optical axis of the lens. After propagating through the lens, this edge mode also propagates in a direction with an angle Ω to the optical axis of the lens, as shown in Fig. 4.1. When the edge mode arrives at the working plane, it is centered at a point with distance a away from the edge of the image of the wide stripe, as shown in Fig. 4.1. The waist radius $w_0{}'$ of the collimated mode can be calculated using Eq. 2.18. The mode size $w(z)$ at the working plane can be calculated using Eq. 2.1, where the propagation distance should be $z = (d - f)/\cos(\Omega) \approx d$, since $d \gg f$ and $\cos(\Omega) \approx 1$. Part of $w(z)$ can stretch out of the image of the wide stripe and contribute to the overall size s of the beam spot at the working plane, as shown in Fig. 4.1.

Now we consider an example. The wide stripe has a half size of $a = 100$ μm, the working distance is $d = 100$ m, the laser mode in the slow axis direction is the same as the mode considered in Sect. 2.5, and the collimating lens has a focal length of $f = 10$ mm, same as the focal length f_1 of the collimating lens used in Sect. 2.5. We have $\Omega = a/f = 100$ μm/10 mm = 10 mR, $a' = 10$ mR × $d = 10$ mR × 100 m = 1 m. $w_0{}'$ was calculated in Sect. 2.5 to be 1.42 mm (the symbol used there is w_{0S}'), we can find $w(z) = 15$ mm at d. Since $w(z) \gg a$, $w(z)$ is approximately centered at the edge of image of the wide stripe. So, the overall spot half size is $s \approx a' + w(z) = 1.015$ m $\approx$ a''. The conclusion is that the size of the image of a wide stripe laser diode is very big and can be used as the overall spot size for the collimated beam of a wide stripe laser diode. Thereby the calculation process can be much simplified.

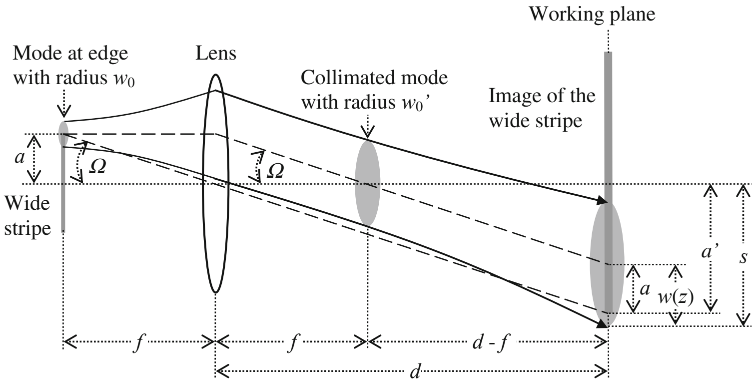

Fig. 4.1 Collimating a multi TE mode laser diode beam using a lens. The dash lines are for geometric optics. The *solid curves* are for the laser mode. The proportion of the drawing is not accurate for illustration purpose

4.1.2 Focusing a Wide Stripe Laser Diode Beam

We consider a case of using one lens to focus the beam of a wide stripe laser diode at a working distance of $d = 500$ mm. The reason of using only one lens to focus the beam is that the beam of wide stripe laser diode is somehow like a geometric light source, it cannot be well collimated or focused to a small spot, as having already being shown in Sect. 4.1.1, a two lens focusing setup shown in Fig. 2.10 is not necessary. The schematic of the focusing situation is shown in Fig. 4.2. The wide stripe, the laser mode and the focusing lens are the same as those used in Sect. 4.1.1. From the geometric optics thin lens equation Eq. 2.12, we find $o = 10.204$ mm will lead to the wide stripe being focused at 500 mm. Then we have from Eq. 4.1 we find $a' = d(a/f) = 4.9$ mm. From the thin lens equation for Gaussian beam, Eq. 2.14, we find $o = 10.204$ mm will lead to the laser mode being focused at 498.9 $\approx$ 500 mm. From Eq. 2.18 we find $w_0' = w_0 \times m = 1.5$ μm $\times$ 48.9 = 73.4 μm. $w_0' < a =$ 100 μm, as shown in Fig. 4.2. So w_0' will not contribute to the overall spot size s, we have $s = a'$. The conclusions drawn here is the save as the conclusion drawn in Sect. 4.1.1, that is the image size of the wide stripe can be used as the overall spot size, the calculation of spot size for a focused beam of a wide stripe laser diode becomes very simple.

4.1.3 Collimating or Focusing a Laser Diode Stack Beam

The schematic of a laser diode stack is shown in Fig. 1.5. The stack can be considered as a rectangular shape geometric light source with size $a \times b$. In the slow axis direction, the spot size of a focused or collimated beam can be calculated using the method described in Sects. 4.1.1 and 4.1.2, with the mode size being

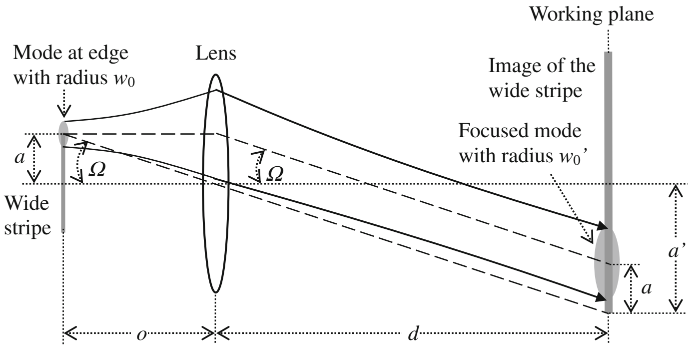

Fig. 4.2 Focusing a multi TE mode laser diode beam using a lens. The dash lines are for geometric optics. The *solid curves* are for the laser mode. The proportion of the drawing is not accurate for illustration purpose

neglected. In the fast axis direction, the mode size is smaller than the mode size in the slow axis direction, thus it's more comfortable to neglect the mode size in the fast axis direction. Eq. 4.1 can be applied to both slow and fast axis directions.

4.1.4 Wide Stripe Laser Diode Beam Shape Evolution

The divergence of a wide stripe multi TE mode laser diode beam is larger in the fast axis direction. If the beam starts with a line shape shown in Fig. 4.3a, as the beam propagates, the beam size in the fast axis direction increases faster than the beam size in the slow axis direction. At one certain distance, the beam shape becomes a square with round corners due to diffraction, as shown in Fig. 4.3b. As the beam continues propagating, the beam shape becomes rectangular with round corners, as shown in Fig. 4.3c. If the beam is focused by a lens, the focused spot is the image of the wide stripe, as shown in Fig. 4.3f, and at certain location in between the lens and the focused image, the beam shape is square as shown in Fig. 4.3e. If the focusing lens is of good quality, we may be able to see the image of these transverse modes in the image line, as shown by black dots in Fig. 4.3f. But more often, image of all these transverse modes merge together because lens aberrations increase the size of the mode image.

4.1.5 Laser Diode Stack Beam Shape Evolution

The shape of a laser diode stack beam evolves as the beam propagates in a way similar to the shape of a wide stripe laser diode beam evolves. Within a few microns to the laser diode stack, the beam has rectangular shape as shown in

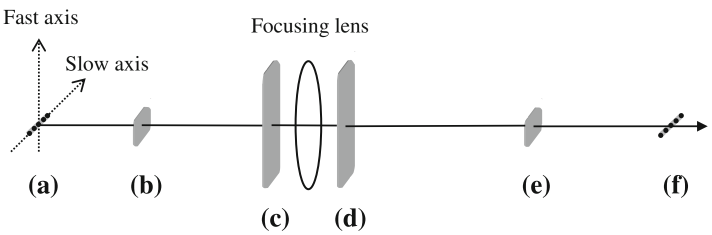

Fig. 4.3 The shape of a wide stripe laser diode beam evolves as the beam propagates in free space and through a lens. The *tiny black dots* in the wide stripe and *image line* represent the transverse modes and their images, respectively

Fig. 4.4a, either a horizontal or vertical rectangle. As the beam propagates, it's shape gradually transforms to a vertical rectangle as shown in Fig. 4.4b. If the beam is collimated or focused by a lens, the image of the laser stack will have a shape similar to the stack as shown in Fig. 4.4d. If the lens is of good quality, we may still be able to see the image of these transverse modes shown by black dots in Fig. 4.4d.

4.2 Fiber Bundle Beam Delivery

A Multi TE mode laser diode beam can be picked up by a multimode fiber array as shown in Fig. 4.5, where a micro lens (glass fiber) of 100 μm diameter or so is used to focus the modes in the fast axis direction onto the fiber array. Multimode fiber has a large core size, often larger than 50 μm. After the modes propagating through the micro lens, the mode sizes in the slow axis direction can still be smaller than the fiber core. Coupling multi TE mode laser diode beam into multimode optic fiber is not as difficult as coupling single TE mode laser diode beam into single mode optic fiber, the coupling efficiency can be high. The fiber array is then rearranged to a circular shape fiber bundle to output a circular multi TE mode beam, as shown in Fig. 4.5, since a circular shape beam is often more desired than a linear shape beam. The beam output from every fiber contains multi TE modes, the output beam from the fiber bundle contains a large number of TE modes. Such a beam is more like a geometric light source than a laser beam. The output beam of fiber bundle can be collimated or focused by a lens. The collimated or focused spot size can be calculated using the technique described in Sect 4.1

4.3 Beam Shaping

The focused spot shape of a wide stripe laser diode is a light line; that is often not desirable. Various beam shaping optical devices have been invented to optically transform the one dimensional light source of wide stripe to a two dimensional

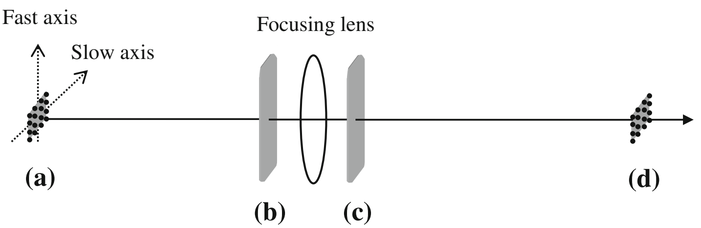

Fig. 4.4 The shape of a laser diode stack beam evolves as the beam propagates. The *tiny black dots* in the laser stack and the image *rectangle* represent the transverse modes and their images, respectively

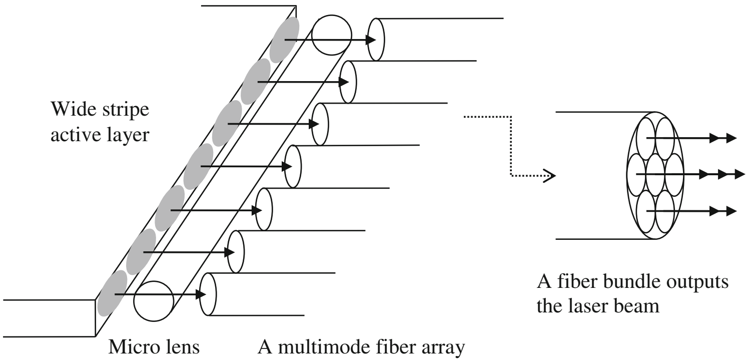

Fig. 4.5 A cylindrical micro lens or glass fiber focuses a multi TE mode laser diode beam into a multimode fiber array, the array then forms a fiber bundle to output a circular shape multi TE mode beam

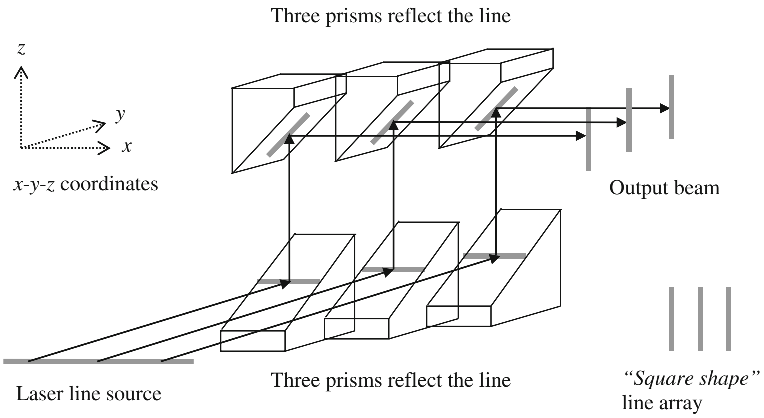

Fig. 4.6 Illustration of a beam shaping prism array. A *laser line* is broken into three sections and forms a "*square shape*" line array

light source. Most such devices are a micro prism array. Figure 4.6 shows an example. A line shape light source propagating in the *y* direction is incident on an array of three micro prisms. The three prisms are position in such a way that they break the light line into three equal length sections and reflect the three light line sections upwards in the *z* direction. Then the three line sections are incident on another array of three micro prisms as shown in Fig. 4.6. The second prism array reflects the three line sections in the *x* direction as the output beam. Looking in the negative *x* direction, we will see the three line sections aligned in parallel and form a "square shape" line array.

The beam shaper shown in Fig. 4.6 is an illustration. There are many patented beam shapers. For example, one beam shaper can transform a light line into five sections and form a "square shape" five line array. Compared with the three line array, the five line array has more even spatial intensity distribution in the direction perpendicular to the lines, and are a better light source for many applications. The difficult task is not only to invent a compact beam shaper on paper, but also to fabricate it at reasonable cost.

Chapter 5
Laser Diode Beam Characterization

Abstract Techniques for measuring single TE laser diode beam size, waist location, M^2 factor, far field divergence and astigmatism are described. Astigmatism measurement is used as an example to illustrate laser diode beam properties.

Keywords Beam profiler · Waist radius · Waist location · M^2 factor · Far field divergence · Astigmatism measurement

Since multi TE mode laser diode beams cannot be well collimated or focused to a small spot, these beams are mainly used in illumination types applications, and do not need be characterized to a high accuracy. Single TE mode laser diode beams are often used in applications where precision collimation or tight focusing is required. Therefore characterizing single TE mode laser diode beams is more important than characterizing multi TE mode laser diode beams. There are many different types of laser diodes, and laser diodes of the same type can have large variations, characterizing single TE mode laser diode beams are of more importance than characterizing the beams of other types of lasers. Single TE mode laser diode beams have large divergence and are almost never directly used. These beams are often collimated or focused by an optical system before being used. Therefore characterizing single TE mode laser diode beams more often means to characterize collimated beams or beams emitted by laser diode modules. In this chapter we only discuss the characterizing the spatial properties of collimated single TE mode laser diode beams, not the spectral or electrical properties. Once the spatial properties of a collimated single TE mode laser diode beam are known, the spatial properties of the beam directly from the laser diode can be back calculated.

Five parameters describe the spatial properties of a single TE mode laser diode beam, they are: beam waist radius in the fast and slow axis directions, respectively, beam waist locations in the fast and slow axis directions, respectively, and the M^2 factor. Wavelength λ is a parameter in the equations describing the spatial properties of the beams and is considered a known parameter.

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5.1 Beam Profiling and Size Measurement

There are two types of laser beam profiler: camera based and scanner based. These beam profilers are mainly used for characterizing laser diode beams since laser diode beams can have various different intensity profiles.

The camera based beam profiler consists of a two dimensional sensing array for catching the beam and a computer loaded with special software for data processing and display. The advantage of using a 2D sensing array is that it can provide a real 2D picture of the beam. Two types of 2D sensor arrays can cover the spectral range from 190 to 1,550 nm, these sensor arrays are easy to find in market and are not expensive. Sensor arrays for longer wavelength can be expensive, that is the disadvantage. Another disadvantage of camera based beam profiler is the relative low resolution limited by the pixel size of a few microns. The software and computer can display various beam parameters, such as $1/e^2$ intensity diameter, $1/e^2$ intensity encircled power, beam center position etc.

The scanner based beam profiler consists of a scanner and a computer loaded with special software for data processing and display. Figure 5.1a shows a widely used knife edge beam scanner. A rotor has a right angle triangle shape knife on it, the beam to be scanned is focused by a lens. The focused beam propagates through the rotor and incidents on a single element sensor. Since the knife has a right angle shape, as the rotor spins, the beam is scanned in two orthogonal directions, as shown in Fig. 5.1b. The beam intensity profiles in these two orthogonal directions can be calculated to a resolution of submicron using the scanner position and the sensor output signal, the resolution is higher than the resolution of pixel based 2D sensing array. It's also less difficult to find different types of single element sensors to cover wider spectral ranges. The disadvantage of a scanning beam profiler is that the beam intensity profiles in the directions other than the two orthogonal scanning directions cannot be directly measured. The computer and software will data fit the beam intensity profiles in these other directions and display the best guess results. The software and computer can display various beam parameters, such as $1/e^2$ intensity diameter, $1/e^2$ intensity encircled power, beam center position etc.

5.2 Locate Beam Waist and Find the M^2 Factor

The measurement can be performed in different ways depending on the situations. Rearranging Eqs. 2.8 and 2.9, we obtain

$$w_0 = \frac{w(z)\pi^{0.5}}{[1 + \frac{w(z)^4\pi^2}{R(z)^2(M^2\lambda)^2}]^{0.5}} \tag{5.1}$$

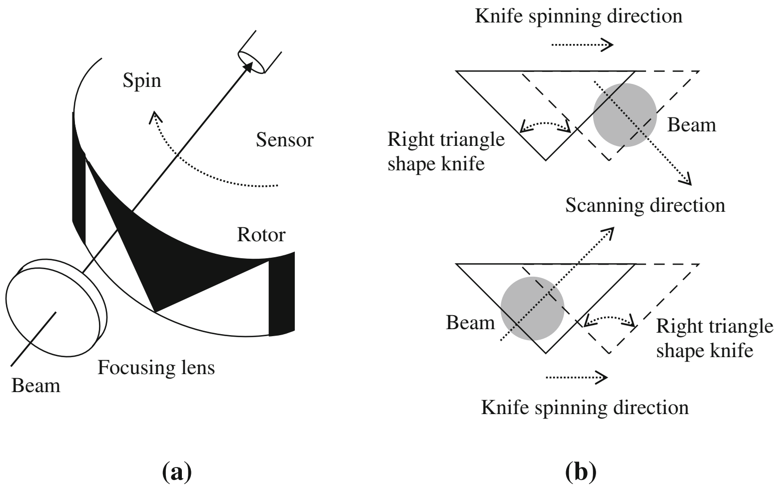

Fig. 5.1 Illustration of a knife edge beam scanner

$$z = \frac{R(z)}{1 + \frac{R(z)^2 (M^2 \lambda)^2}{w(z)^4 \pi^2}} \tag{5.2}$$

Equations 5.1 and 5.2 indicate that if we have measured the beam radius $w(z)$ and the beam wavefront radius $R(z)$ at certain point, and know the wavelength λ and the M^2 factor, we can calculate the beam waist radius w_0 and the distance z between the beam waist and this certain point. Measuring the beam size is relatively simple as shown in the above section. Unfortunately, measuring the wavefront radius requires the use of an interferometer that is often not available in many labs.

If we have measured the beam radius $w(z)$ at certain point, know the beam waist radius w_0, and know the wavelength λ and the M^2 factor, we can calculate the distance z between the beam waist and this certain point by modifying Eq. 2.8

$$z = \frac{w_0 \pi}{M^2 \lambda} [w(z) - w_0]^{0.5} \tag{5.3}$$

Similarly, if we have measured the beam radius $w(z)$ at certain point and know the distance z between this certain point and the beam waist, and know the wavelength λ and the M^2 factor, we can calculate the beam waist radius w_0 by modifying Eq. 2.8 to

$$w_0 = \frac{w(z)}{2^{0.5}} \{1 + [1 - (\frac{2\lambda z M^2}{\pi w(z)^2})^2]^{0.5}\}^{0.5} \quad (z \le z_R) \tag{5.4}$$

or

$$w_0 = \frac{w(z)}{2^{0.5}}\{1 + [1 - (\frac{2\lambda z M^2}{\pi w(z)^2})^2]^{0.5}\}^{0.5} \quad (z \geq z_R) \tag{5.5}$$

Equations 5.4 and 5.5 are applicable to near field and far field, respectively. When $z = z_R$, $w(z) = 2^{0.5}w_0$, term $2\lambda z M^2/[\pi w(z)^2] = 1$, Eqs. 5.4 and 5.5 become the same. But, since in this case, we don't know w_0 and z_R, and don't know whether we are at the near field or far field, we have to use both Eqs. 5.4 and 5.5 to calculate two values for w_0, then insert these two values of w_0 into Eq. 2.8 to see which value of w_0 will result in a $w(z)$ that matches the measured result.

In most cases encountered, we know neither the beam waist radius w_0, nor the beam waist location, nor the M^2 factor, we only know the wavelength λ. Then the practically best way is simply to move the beam profiler along the beam to find the beam waist radius w_0, estimate the Rayleigh range z_R for this beam waist, then measure the beam radius $w(z)$ at far field with distance $z \gg z_R$. The M^2 factor can be calculated from Eq. 2.11 using the measured w_0 and $w(z)$ and the known z.

Here we would like to note that ISO 11146 procedure specifies the method of measuring the M^2 factor. The ISO procedure requires that the ten beam sizes along the beam propagation axis are measured. Among the ten measurements, five are around the beam waist and five are at least two Rayleigh ranges distance away. Since laser diode beams have large divergence, a collimated or focused beam usually has a waist radius from 0.5 to 5 mm. For a beam with 1.5 mm waist radius, 0.67 μm wavelength and a $M^2 = 1.1$, the Rayleigh range can be found from Eq. 2.10 to be $z_R \approx 9.6$ m. Twice the Rayleigh range makes 19.2 m; that is a long distance inside a lab. For a laser diode beam without being manipulated, the Rayleigh range is only several microns, a commonly used beam profiler cannot be positioned that close to the laser diode facet, and the distance between the laser diode facet and the beam profiler sensing surface cannot be determined to a submicron accuracy. All the beam profiler can find is the far field beam pattern and only coarse measurement can be performed.

However, if we collimate a laser diode beam using a good lens, measure the waist radius of the collimated beam, and know the collimating lens focal length and laser wavelength, we can back calculate the waist radius and divergence of this laser diode beam. Such a characterization is easier to perform and the results are more accurate compared with directly characterizing the laser diode beam.

5.3 Beam Far Field Divergence Measurement

For a collimated or focused laser diode beam, once we have measured the beam waist radius and the beam radius at far field, the beam far field divergence can be calculated using Eq. 2.11. There is another way to measure the far field divergence of a laser diode beam without the need to measure the beam waist radius. Figure 5.2 shows a setup to measure the far field divergence of a collimated laser diode beam,

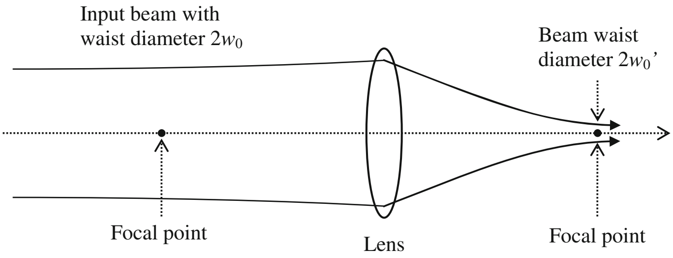

Fig. 5.2 A setup for measuring the far field divergence of a laser diode beam

where a lens with known focal length f focuses this beam. For a typical collimated laser diode beam, the Rayleigh range z_R is several meters, a typical lens focal length is $\sim$ 10 mm, we have $z_R/(M^2 f) \gg 1$ and obtain $i \approx f$ from Eq. 2.14. Also because $z_R/(M^2 f) \gg 1$, we can obtain from Eqs. 2.18 and 2.11 that

$$\begin{aligned} \frac{w_0'}{f} &= \frac{w_0}{z_R} \\ &= \theta \end{aligned} \tag{5.6}$$

Eqution 5.6 tells us that we can find the far field divergence θ of a collimated laser diode beam by focusing the beam and measuring the waist radius of the focused beam.

5.4 Astigmatism Measurement

When people talk about the astigmatism in laser diode beams, they mean the beams without being manipulated. Once we know the astigmatism, the astigmatism in collimated or focused beams can be calculated. Single TE mode laser diodes have astigmatism of several microns in magnitude. Most laser diodes have their beam waist in the slow axis direction located behind the beam waist in the fast axis direction, as shown in Fig. 1.1, although there was opposite case reported. Several microns is a small value to measure. The elliptical shape and Gaussian nature of laser diode beams make the measurement more complex. If the measurement is not performed carefully, there can be large errors or even erroneous measurement result. Astigmatism measurement touches all the aspects of single TE mode laser diode beams and can be used as a good example to demonstrate the characteristics of laser diode beams.

In this section, we analyze an example. We consider a laser diode with parameters given in Sect. 2.5; the 1/e^2 intensity beam waist radii are $w_{0F} = 0.5$ μm and $w_{0S} = 1.5$ μm in the fast and slow axis direction, respectively, the wavelength is $\lambda = 0.67$ μm and the $M^2 = 1$. Figure 5.3 shows a setup for astigmatism measurement,

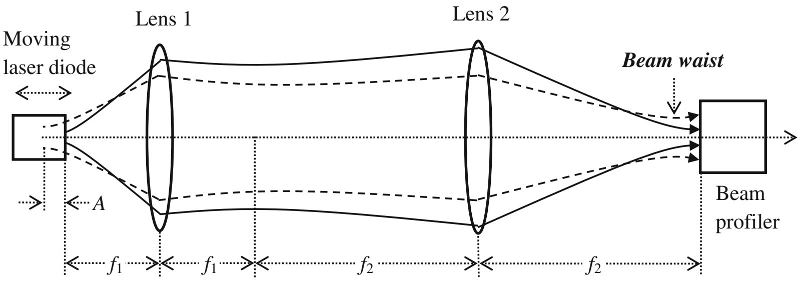

Fig. 5.3 A setup for astigmatism measurement. The *solid* and *dash curves* are for the beam in the fast and slow axis directions, respectively

where lens 1 with focal length $f_1 = 10$ mm collimates the laser beam and lens 2 with focal length $f_2 = 100$ mm focuses the laser beam. This setup is the same as the one shown in Fig. 2.10. Lens 1 must have large numerical aperture so that it does not clip the beam, otherwise the beam clipping may cause focal shift and large error to the measurement result. The spacing d between the two lenses should be $d \approx f_1 + f_2$. A beam profiler is positioned at the 2nd focal plane of lens 2. The laser diode to be measured is positioned around the 1st focal plane of lens 1. During the measurement, the laser diode is moved back and forth along the optical axis. When the waist of the laser diode beam in the fast axis direction is at the 1st focal plane of lens 1, the beam profiler will see the focused spot in the fast axis direction, the situation is shown in Fig. 5.3; the position of the laser diode is recorded. When the waist of the laser diode beam in the slow axis direction is at the 1st focal plane of lens 1, the beam profiler will see the focused spot in the slow axis direction, the position of the laser diode is recorded again. The distance between the two positions of the laser diode is the astigmatism. This measurement method can be called "moving laser diode method".

The reason of choosing $f_2 \gg f_1$ is that the longitudinal magnification ratio of the two lenses is $(f_2/f_1)^2$. For a large magnification ratio, the same amount of position change for the laser diode will cause larger focused spot size change at the 2nd focal plane of lens 2 and make the measurement easier. The reason of letting $d \approx f_1 + f_2$ is that when the beam waist of the laser diode is at the 1st focal plane of lens 1, the waist of the beam collimated by lens 1 will appear at the 2nd focal plane of lens 1 and at the 1st focal plane of lens 2, and the spot of the beam focused by lens 2 will appear at the 2nd focal plane of lens 2. That is the situation we want. If $d \neq f_1 + f_2$, the waist of the beam collimated by lens 1 will not appear at the 1st focal plane of lens 2, then the spot of the beam focused by lens 2 will not appear at the 2nd focal plane of lens 2, and results in measurement error, that is the ghost astigmatism phenomenon discussed in Sect. 2.5. However, it can be shown that in this case a 450 mm error in setting d will only cause an error of 0.5 µm in astigmatism measurement. Generally speaking an error smaller than 100 mm in d is good enough. $d \approx f_1 + f_2$ will also make the measurement setup optically simpler in case there are problems need be analyzed.

The measurement error of the moving laser diode method can be so estimated. If the beam waist in the fast axis direction is positioned 10.001 mm away from lens 1 (a 1 μm positioning error), using Eq. 2.14 we can find the waist of the collimated beam in the fast axis direction will appear at 42.13 m from lens 1 (at the right hand side of lens 1), or $f_1 + f_2 - 42.13$ m = −42.02 m to lens 2 (also at the right hand side of lens 2). Then the radius of the spot focused by lens 2 in the fast axis direction can be calculated from Eq. 2.18 to be 9 μm, that is about half the best focused spot radius of $w_{0F}'' = 18$ μm (see Sect. 2.5), and is quite a big change. If the beam waist in the slow axis direction is positioned 10.001 mm away from lens 1 (a 1 μm positioning error), using Eq. 2.14 we can find the waist of the collimated beam in the slow axis direction will appear at 0.9 m from lens 1 (at the right hand side of lens 1), or $f_1 + f_2 - 0.9$ m = −0.79 m to lens 2 (also at the right hand side of lens 2). Then the radius of the spot focused by lens 2 in the slow axis direction can be calculated from Eq. (2.18) to be 67 μm, that is about 7 % smaller than the best focused spot radius of $w_{0S}'' = 72$ μm (see Sect. 2.5). That kind of spot size change should be noticeable. So, the measurement accuracy of moving diode method with this setup is about 1 μm.

By principle, astigmatism can also be measured by positioning one of the two beam waists of the laser diode at the 1st focal plane of lens 1 and moving the beam profiler back and forth along the optical axis around the 2nd focal plane of lens 2. The beam profiler is expected to see two focused spots in the fast and slow axis direction, respectively, at two locations. The distance *A'* between the two locations of the beam profiler can be used to back calculate the astigmatism *A* by

$$A = A'(f_1/f_2)^2 \tag{5.7}$$

This measurement method can be called “moving profiler method”. Some widely circulated technical notes also recommend this moving profiler method.However, there is a potential big problem for moving profiler method. To explain this, we plot the third quadrant of Fig. 2.11 in Fig. 5.4 for more details; that is the *i* versus *o* curve for lens 1. Assume we position the beam waist of the laser diode in the slow axis direction at the 1st focal plane of lens 1 and move the beam profiler to find the focused beam spot in the fast axis direction. From Fig. 5.4 we can see that one *i* value in the fast axis direction correspond to two values for *o*. The solid and open dots in Fig. 5.4 show only two such examples. That means two waist positions of the laser diode beam at the left hand side of lens 1 will lead to the same waist positions at the right hand side of lens 1 and same waist spot positions at the right hand side of lens 2. Therefore, the measurement result can be erroneous. This is also a kind of ghost astigmatism unique to the elliptical beams of laser diodes.

To avoid such a problem, the waist of the laser diode beam in the fast axis direction must be positioned at the 1st focal plane of lens 1, and the beam profiler is moved back and forth to find the focused spot in the slow axis direction. Then we can see from Fig. 5.4 that the *i* versus *o* curve in the slow axis direction is not linear and almost flat for astigmatism larger than 8 μm or so, where a couple of microns difference in astigmatism will not lead to a noticeable change in *I* (the

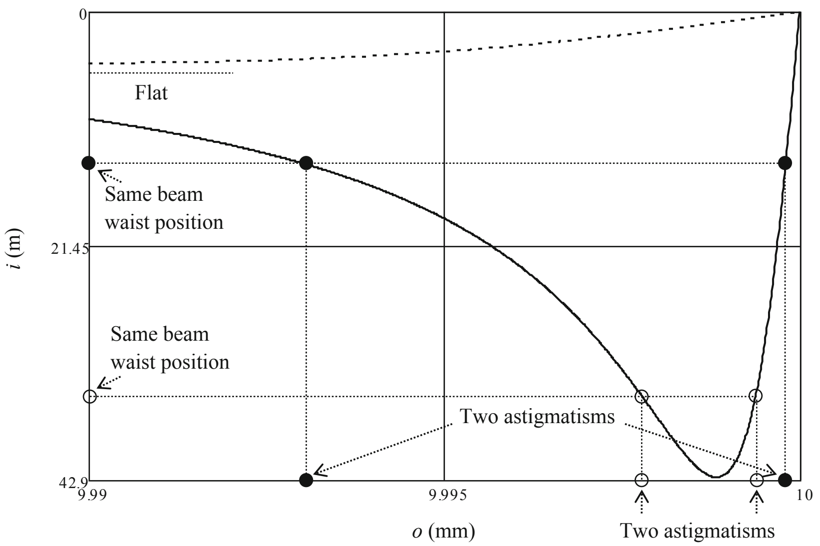

Fig. 5.4 *Solid* and *dash curves* are *i* versus *o* curves in the fast and slow axis directions, respectively, for lens 1. The *solid* and *open dots* show that different astigmatisms can result in the same focused spot positions and erroneous measurement results

waist position at the right hand side of lens 1), and will not lead to a noticeable in the position of the spot focused by lens 2, the measurement result will be of low accuracy.