Design of coupling system in fiber optic sensing measurement

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Abstract: According to the principle of choosing the light source in the fiber optic sensing measurement, semiconductor laser is used as the light source of fiber optic sensor and single-mode fiber is used as the tail fiber of light source. Based on optical design software Zemax's pure non-sequential components, a coupling system of semiconductor laser and single-mode fiber is designed. By analyzing the beam characteristics of the semiconductor laser and the coupled mode theory of semiconductor laser and single-mode fiber, the combined lens consists of a ball lens and a collimating lens for the purpose of improving the coupling efficiency and adjusting tolerance. The simulation results show that the coupling efficiency can reach about 78% by using one million ray traces on non-sequential components, while the experimental test result is 69.11%, accordingly, the reasons for the difference between the experiment and the simulation results are analyzed.

Key words: semiconductor laser; fiber couple; Zemax; coupling efficiency

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0 Introduction

The light source is an important part of fiber optic sensing measurement system. To a great extent, its type and performance determine the measuring accuracy of a sensor system. The primary principle of selecting a light source for a reflective intensity modulation fiber optic sensor(RIM-FOS) is that the output power should be stable. In addition, the light source should be easily coupled with fiber[1]. Considering the structure of the RIM-FOS, semiconductor laser usually is used as light source. To obtain a better lateral resolution, we generally select single-mode fiber as tail fiber. But the core diameter of single-mode fiber is small, therefore the coupling between laser and fiber plays a key role in fiber optic sensing measurement system.

At present, semiconductor laser and fiber coupling technology has been developed to a certain mature stage[2-4]. Especially, in the coupling of semiconductor laser with multi-mode optic fiber, many effective methods with high coupling efficiency have been proposed, such as the coupling system designed by Shi, et al. based on Zemax, whose efficiency is about 68%[5]; a semiconductor laser with trench structure proposed by Cui, et al. to stabilize the coupling efficiency and raise it to 97.7%[6]. But the core diameter of a single-mode fiber is approximately equal to the dimension of the active layer light emitting end of semiconductor laser, with micrometer scale. Therefore, different from the multi-mode fiber coupling system, the laser light-emitting facet cannot be approximated as a point source[7]. The major factors affecting the coupling efficiency between semiconductor laser and single-mode fiber include mode field mismatch between laser and fiber, non-circular symmetry of output beam, mismatch of mode-field-half-width, Fresnel reflection on surface and aberration of the coupling lens[8]. A variety of efficient coupling methods hitherto have been proposed, which can be summed up into two types: a coupling system composed of discrete micro optical elements or micro-lenses on the fiber's end face[9-11]. The ultimate aim of these methods is to couple the elliptical mode field of laser into the circular mode field of single-mode fiber as much as possible. Among these methods, the ball lens is the simplest to be easily manufactured because its own

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circular symmetry makes it much easier to set up than other lenses and then the ball lens coupling becomes one of the most common methods of mode field coupling between laser and single-mode fiber[12-13]. This paper presents a combined lens coupling system. After added a collimating lens to collimate the laser beam, the ball lens focuses the beam into a single-mode fiber. Based on Zemax pure non-sequential components, the coupling efficiency by simulation can reach about 78%.

1 Fiber coupled mode field theory

In theory, the maximum coupling efficiencies of semiconductor laser and single-mode fiber depend on their mode matching. The mode field distribution of single-mode fiber is circular and symmetrical, and its distribution can be deduced to be a Gaussian distribution using electromagnetic theory[14]. Therefore, single-mode fiber end face mode field distribution expression is

$$\psi_f(x,y)=\sqrt{\frac{2}{\pi}}\,\frac{1}{\omega_f}\exp\left(-\frac{x^2+y^2}{\omega_f^2}\right), \tag{1}$$

$$\omega_f=a(0.65+1.619V^{\frac{-2}{3}}+2.879V^{-6}), \tag{2}$$

where $V=k_0a\sqrt{n_1^2-n_2^2}$; ω_f is the mode field radius of the single-mode fiber; V is the normalized cutoff frequency; n_1 is the core refractive index; n_2 is the cladding refractive index; and k_0 is the wave vector in the vacuum.

The mode field distribution of the semiconductor laser is more complicated and can be divided into near-field distribution and far-field distribution. In the design of semiconductor laser structure, the asymmetry of the cross-section of source layer may cause the asymmetry of far-field spot, so the output beam can be approximated as a bundle of asymmetric Gaussian beams[15]. As shown in Fig. 1, the light field of semiconductor laser has an elliptical and symmetric distribution and its divergence angle perpendicular to the p-n junction plane is larger than that parallel to the p-n junction plane.

According to electromagnetic theory, the output laser beam can be approximated as a Gaussian beam with a beam waist position at the laser end face, and the mode field distribution is expressed as

$$\psi_o(x,y)=\sqrt{\frac{2}{\pi}}\,\frac{1}{\sqrt{\omega_{0x}\omega_{0y}}}\exp\left[-\left(\frac{x^2}{\omega_{0x}^2}+\frac{y^2}{\omega_{0y}^2}\right)\right], \tag{3}$$

$$\psi_o(x,y,z)=\sqrt{\frac{2}{\pi}}\,\frac{1}{\sqrt{\omega_{zx}\omega_{zy}}}\exp\left[-\left(\frac{x^2}{\omega_{zx}^2}+\frac{y^2}{\omega_{zy}^2}\right)\right]\times \exp\left[-ik\left(z+\frac{x^2}{2R_{zx}}+\frac{y^2}{2R_{zy}}\right)+\frac{i}{2}(\varphi_{zx}+\varphi_{zy})\right], \tag{4}$$

where $\omega_{zx}=\omega_{0x}\sqrt{1+\left(\frac{z}{f_{ox}}\right)^2}$; $f_{0x}=\frac{\pi\omega_{0x}^2}{\lambda}$; $R_{zx}=z+\frac{f_{0x}^2}{z}$.

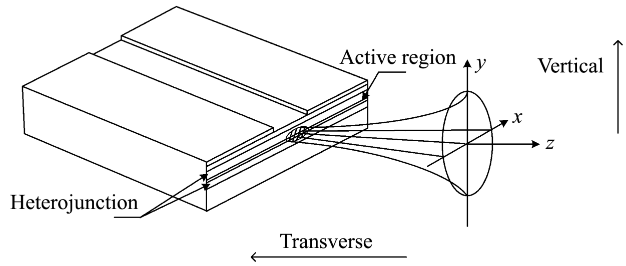

Fig. 1 Far-field distribution of semiconductor laser

Eq. (3) represents the near-field distribution of semiconductor laser; ω_{0x} and ω_{0y} respectively represent the beam waist radii in the x and y directions of the cavity. Eq. (4) represents the far-field distribution of semiconductor laser; ω_{zx} and ω_{zy} respectively represent the waist radii in the x and y directions of the light after transmitting z distance along the z-axis; R_{zx} and R_{zy} respectively represent the wavefront curvature radii of the light in the x and y directions after transmitting z distance along the z-axis; φ_{zx} and φ_{zy} represent the additional phase shift of the light in the x and y directions after transmitting z distance along the z-axis; f_{0x} represents the confocal parameter of Gaussian beam; and λ represents the wavelength of semiconductor laser.

Based on the mode field distribution functions of single-mode fiber and semiconductor laser, the coupling efficiency between fiber and laser can be obtained by calculating the overlap integral of mode field as[16]

$$\eta=\eta_T\eta_C=\frac{\left|\iint\psi_z^*\psi_f\,dA\right|^2}{\int_{-\infty}^{+\infty}\psi_f\psi_f^*\,dA\int_{-\infty}^{+\infty}\psi_z\psi_z^*\,dA}, \tag{5}$$

where η_T is the system transmission rate, calculated as 1. Actually, in the coupling process, since the optic fiber end face has a certain angle or radius of curvature after processing, an angular function and a curvature radius function need to be added in the calculation to obtain a more accurate calculation result.

2 Coupling system design

According to fiber-coupled mode field theory, the coupling between semiconductor laser and single-mode fiber is an essential mode field matching. Due to the elliptical Gaussian distribution of the outgoing laser field of the semiconductor laser, if the direct coupling method is adopted, the mode field mismatch between them will lead to only about 10% of the coupling efficiency. Therefore, the output light field of the semiconductor laser should be shaped to match the mode field of the single-mode fiber, so as to reduce the loss caused by the coupling between the laser and the optic fiber.

Optic fiber and semiconductor laser coupling technology can be divided into three categories according to the structures: single-lens coupling, combination lens coupling and optic fiber micro-lens coupling. Due to the limitation of the single-lens optic characteristics, the single-lens coupling method is simple in structure, but it has a relatively small tolerance and is difficult to be calibrated. For the coupling method of optic fiber micro-lens, it is relatively difficult to be processed. Therefore, the combination lens coupling method is adopted to improve the coupling efficiency and to adjust the tolerance. Semiconductor laser and single-mode fiber coupling schematic is shown in Fig. 2.

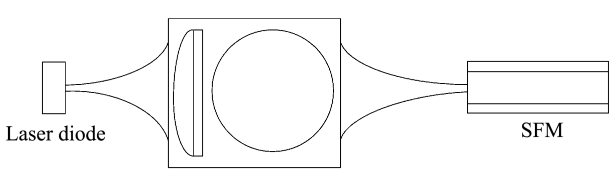

Fig. 2 Principle of coupling system

The optical design software Zemax was used to simulate the coupling system. Assuming that both the fast and the slow axis divergence angles reach their maximum, the specific parameters of the simulation are as follows: the center wavelength of the semiconductor laser is 1 550 μm, the power is 1 W, the divergence angle of the fast axis (perpendicular to the junction plane) is less than 35°, the divergence angle of the slow axis (parallel to the junction plane) is less than 18°, the fiber mode field diameter is 9 μm and the effective group refractive index is 1.467. The 3D layout of coupling system is shown in Fig. 3.

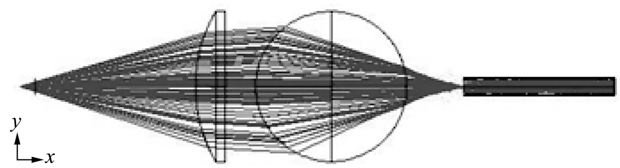

Fig. 3 3D layout of coupling system design

The coupling system consists of a collimating lens and a ball lens. The semiconductor laser emits collimated light through a collimating lens, and then the light is focused into a single-mode fiber through a ball lens. The lenses are made of BK7 material, and each glass is coated with anti-reflective coating. The default fiber cladding property is "absorb". The detector is placed at the end of the optic fiber with z=5 μm from the exit end of the light source. The size of the detector is 10 μm×10 μm and the property is "absorb". By Zemax non-sequential ray tracing, the corresponding spot maps in the two detectors are shown in Figs. 4 and 5, respectively.

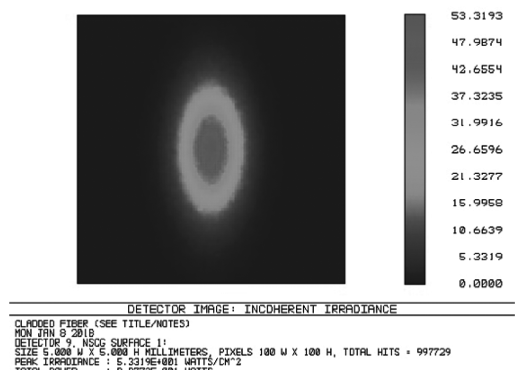

Fig. 4 Spot map of detector 1

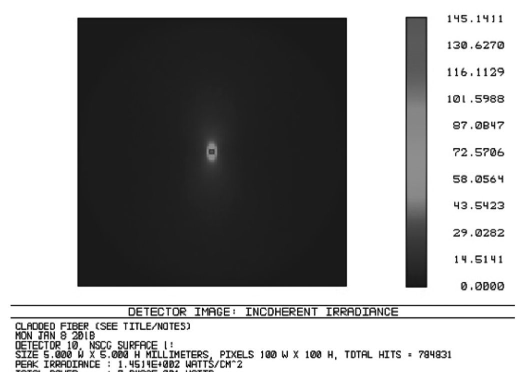

Fig. 5 Spot map of detector 2

It can be seen from Figs. 4 and 5 that the exit spot of the semiconductor laser has an elliptical Gaussian distribution with a light source energy of 0.998 W at a distance of 5 μm from the exit end of the light source. When the output beam of the coupling system enters the optic fiber, the energy gained by the detector is 0.784 W. The spot area is obviously reduced and the distribution is circularly symmetrical, which matches the mode field of the single-mode fiber. The coupling efficiency obtained by the fiber coupling formula is 78.4%. As the divergence angle of the actual value is less than the design value, so the system coupling efficiency should be greater than 78.4%.

3 Analysis of experimental results

When the working current of the semiconductor laser is changed at room temperature, the output light powers of the laser before and after shaping are measured, so does the output light power of the transmission fiber coupled with the laser. According to these test data, the coupling efficiency can be calculated, as shown in Table 1.

Table 1 Output powers of semiconductor laser before and after coupling and coupling efficiency at different working currents

Working current (mA)	Pre-shaping power (mW)	Shaped power (mW)	Fiber output power (mW)	Coupling efficiency (%)	Overall coupling efficiency (%)
10	2.31	1.74	1.61	75.32	69.70
20	4.55	3.39	3.13	74.51	68.79
30	6.72	5.02	4.59	74.70	68.30
40	8.91	6.68	6.24	74.97	70.03
50	10.90	8.21	7.59	75.32	69.63
60	12.97	9.71	8.93	74.87	68.85
61.8	13.26	9.84	9.08	74.21	68.48

It can be found from Table 1 that when the working current reaches a maximum value of 61.8 mA, the actual output power after coupling is 9.08 mW, and the overall coupling efficiency is 68.48%. Fig. 6 shows the semiconductor laser *P*-*I* curve and overall coupling efficiency curve from an experimental test.

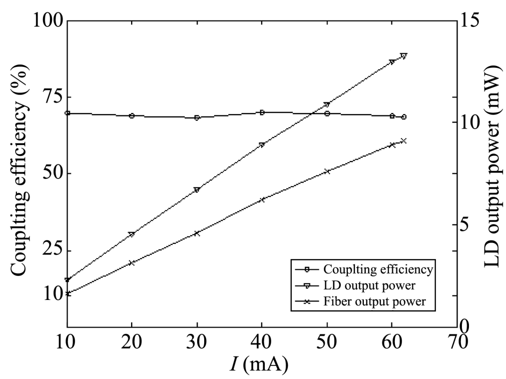

Fig. 6 Semiconductor laser *P*-*I* curve and overall coupling efficiency curve from an experimental test

The overall coupling efficiency is more than 68.30% in the actual test, but the coupling efficiency of the theoretical simulation is 78.4%. There is certain a gap between the simulation value and the actual value. The main errors are as follows:

1) Optic fiber error. The propagation loss of the beam in the optic fiber is not considered when using Zemax for simulation. The fiber used in the experiment has a certain transmittance, within the range of 90%−99%. Therefore, some of the light energy will be lost during the actual transmission.

2) Coupling error. There are many optical surfaces in the experiment, and the processing error and the relative position error between each optical element will reduce the coupling efficiency.

3) Shaping error. Due to the deviation of the shaping and adjustment of the shaping device, the quality of the shaped beam has some differences to the theoretical simulation. For example, the beam divergence angle may be slightly larger than the simulation value, thus this will affect the actual coupling efficiency.

4 Conclusion

Aiming at the problem of light source coupling in fiber optic sensing measurement, this paper establishes the coupled mode field theory model of semiconductor laser and single-mode fiber, designs a coupling system to improve coupling efficiency, adjust tolerance, and reduce the loss of light source power in fiber optic sensing measurement. The system uses a combination lens consisting of a collimating lens and a ball lens. And based on Zemax pure non-sequence, the simulation results show that the coupling efficiency can reach about 78%. The experimental results show that the overall average coupling efficiency is 69.11%. This is because the optical fiber transmission loss and the error caused in the process of encapsulation will make the actual coupling efficiency deviate from the theoretical design value.

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光纤传感测量中耦合系统的设计

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摘　要: 根据光纤传感测量中光源的选取原则, 将半导体激光器作为光纤传感器的光源并选取单模光纤作为尾纤, 基于光学设计软件 Zemax 纯非序列光学系统, 设计了一种半导体激光器与单模光纤的耦合系统。通过分析半导体激光器的光束特性及半导体激光器与单模光纤的耦合模场理论, 由一个球透镜和一个准直透镜构成组合透镜耦合方式, 达到提高耦合效率和容忍度的目的。设计时在非序列光学系统下进行了百万次光线追迹, 仿真得到所设计系统的耦合效率为 78%左右, 而实验测试结果为 69.11%, 由此对误差产生的原因进行了分析。

关键词: 半导体激光器; 光纤耦合; Zemax; 耦合效率

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