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A new tapered semiconductor laser with integrated multimode interference coupler

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A new tapered semiconductor laser with an integrated multimode interference coupler is presented in this paper. The seed source of the new laser is a multimode interference coupler semiconductor laser, which overcomes the limitations imposed by the relationship between single mode output and gain medium volume in the ridged waveguide region. The simulation results show that the multi-mode interference coupler can effectively provide a spatial single-mode seed light source for the tapered output waveguide, and the tapered output waveguide of the tapered semiconductor laser can also effectively reduce the optical power density of the output laser, which verifies the feasibility of the design scheme and provides a new idea for the design of high beam quality and high power tapered semiconductor laser.

KEYWORDS

tapered semiconductor laser, multimode interference coupler, high power, high beam quality, far-field output characteristics

1 Introduction

Semiconductor lasers with high power and high beam quality have important applications in laser communication, industrial production and other fields. Traditional high-power semiconductor lasers have weak side mode restriction and unstable mode, beam quality factor (M^2, $1/e^2$) is more than 15, and brightness is less than 10 MW $\cdot cm^{-2} \cdot sr^{-1}$ [1]. In order to improve the beam quality, slab coupled optical waveguide lasers, external cavity lasers, inclined cavity lasers and tapered lasers have been proposed [2–4]. Among them, the tapered semiconductor laser can not only achieve high power output and high beam quality output, but also have the advantage of high integration, so it has been widely studied [1]. Typically, a tapered semiconductor laser consists of a ridge waveguide region and a tapered waveguide region. The ridge waveguide region serves as the master oscillator, producing low-power lasers with excellent mode quality, while the tapered waveguide region acts as the slave oscillator for laser power amplification. The tapered waveguide region provides a larger surface area, effectively reducing the optical power density of the emitted laser while ensuring high-power output to prevent any potential damage on the cavity surface caused by optical disasters [5]. In order to provide a spatial single-mode seed light source, the width of the ridge waveguide region

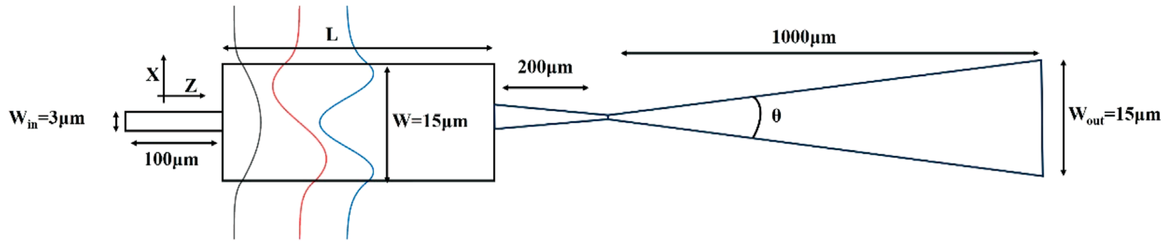

FIGURE 1
Schematic diagram of the waveguide structure of the new tapered semiconductor laser with integrated multimode interference coupler.

is usually smaller than the single-mode cutoff condition, but this results in a smaller gain medium volume in the ridge waveguide region and a smaller laser energy provided to the tapered waveguide region. Therefore, how to increase the gain medium volume while ensuring the single mode output in the ridge waveguide region becomes one of the keys to improve the output power of the tapered semiconductor laser. Multimode interference (MMI) couplers based on self-imaging effect have the advantages of large area of multimode waveguide and compact structure, and are commonly used as basic devices in integrated optics [6–9]. In recent years, many domestic and foreign scholars have used multi-mode interference couplers to design semiconductor lasers to overcome the waveguide width limitation while maintaining stable single-mode output. Currently, the output power of multi-mode interference couplers semiconductor lasers can reach hundreds of milliwatts [10–12]. Therefore, a multimode interference coupler semiconductor laser is proposed as the seed source of a tapered semiconductor laser to break through the restricted relationship between the single mode output and the gain medium volume in the ridged waveguide region.

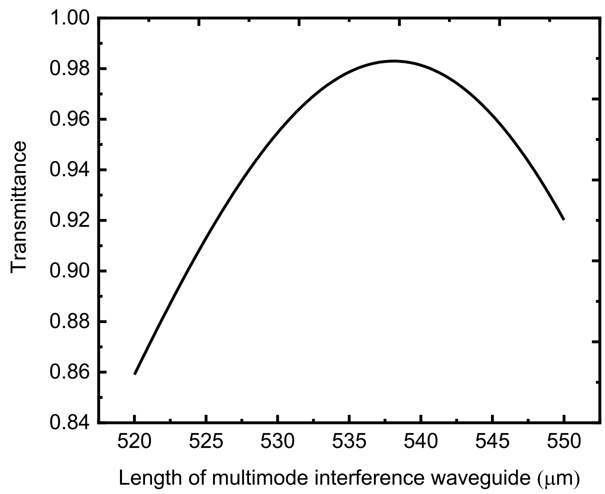

FIGURE 2
The relationship between the transmittance of 1 × 1 MMI and the length of multimode interference waveguide.

2 Design and simulation

The waveguide structure of the new tapered semiconductor laser is composed of a multi-mode interference coupler and a taper output waveguide, as shown in Figure 1.

The tapered output waveguide is the key area for power amplification of the tapered semiconductor laser. In order to achieve efficient energy transmission, according to the adiabatic coupling theory, the taper angle θ of the refractive index guided tapered amplification region is generally less than 1°, and may be as small as a few tenths of a degree, so as to ensure that the low-order mode in the input waveguide is gradually transformed into the low-order mode in the cone waveguide region [8, 13, 14]. The purpose of this paper is to verify whether the multimode interferometric coupler semiconductor laser can be used as the seed source of the tapered semiconductor laser, the length of the tapered output waveguide is set to a fixed value of 1000 μm, the width of the output waveguide is set to a fixed value of 15 μm, and the width of the input end is the same as that of the output end of the multi-mode interference coupler, at this point, the taper angle of the tapered output waveguide is approximately θ~0.4°.

The multimode interference coupler comprises three components: the input straight waveguide, the multimode interference waveguide, and the output tapered waveguide. The incident wavelength is set at 1.55 μm, the effective refractive index of the waveguide ridge region is n_r = 3.2453, and the effective refractive index on both sides of the ridge region is n_c = 3.2027. These simulation parameters are taken from the literature [10]. To minimize the number of modes within the input waveguide while taking into account the difficulty of the lithography process, the width of the ridge region of the input waveguide is set at 3 μm, its length is 100 μm. Rsoft's BeamPROP module is based on advanced finite-difference beam propagation (BPM) technology that allows the user to define the material properties and structural geometry of the device, therefore, all simulations in this paper are based on the BeamPROP module. Using the mode calculation function of BeamPROP module, there are three guided wave modes with effective refractive indices of 3.239,405, 3.222,708, and 3.202,781 within the input waveguide. However, only the fundamental mode of the input waveguide forms a single image of equivalent mode volume at the output end of the multimode interference waveguide, so the waveguide width at one end of the output cone waveguide is set to 3 μm. The output light field of the output tapered waveguide acts as the single mode seed source of the tapered semiconductor laser, so the width of the other end of the output tapered waveguide

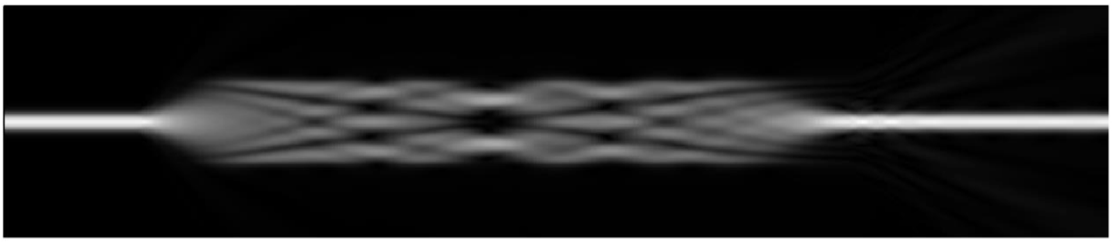

FIGURE 3
Diagram of the field distribution in 1 × 1 MMI.

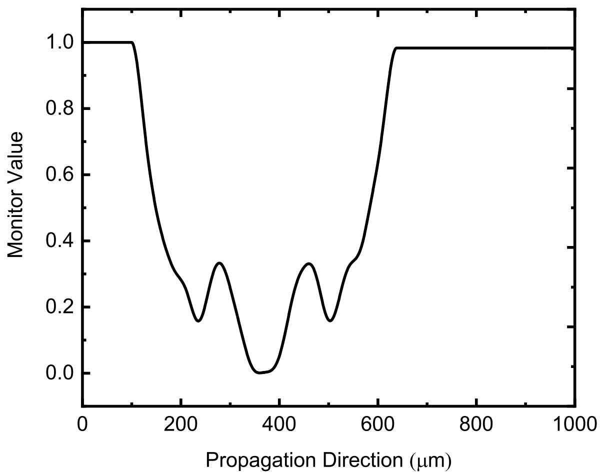

FIGURE 4
The total field strength in a region of 3 μm equal width to the input waveguide along the 1 × 1 MMI z-axis.

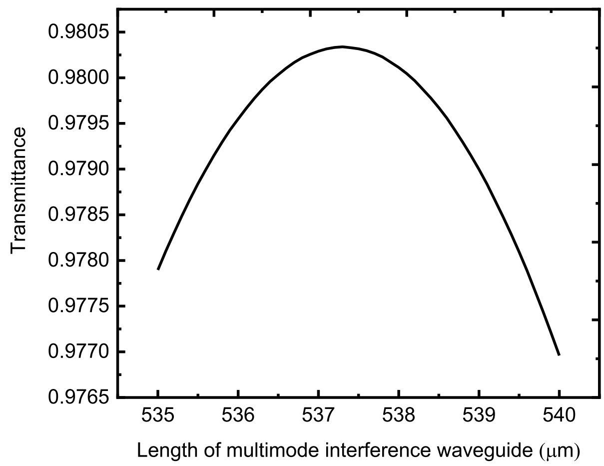

FIGURE 6
The relationship between the transmittance of the new semiconductor tapered laser and the length of multimode interference waveguide.

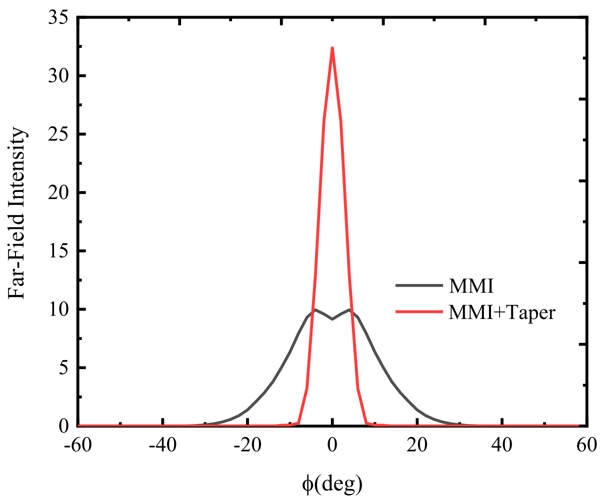

FIGURE 5
Comparison of the far-field distribution between conventional MMI laser and new semiconductor tapered laser.

is set to 1 μm to ensure that its single mode output has a stronger diffraction effect, and the tapered output waveguide can have a larger taper angle [14]. The length of the output tapered waveguide is set to 200 μm to ensure the conversion of different modes at both ends of the output waveguide.

Multimode interference waveguide is one of the keys to design MMI. The ridge width of the multimode interference waveguide is set to W = 15 μm, the effective refractive indices of ν = 11 guided wave modes $\psi_\nu(x)$ in the waveguide are 3.244936, 3.243844, 3.242026, 3.239485, 3.236227, 3.232259, 3.227595, 3.222259, 3.216296, 3.20981 and 3.20331, respectively. The first three guided wave modes are illustrated in Figure 1. When ν is even, $\psi_\nu(-x) = \psi_\nu(x)$, $\psi_\nu(x)$ is even mode, and when ν is odd, $\psi_\nu(-x) = -\psi_\nu(x)$, $\psi_\nu(x)$ is odd mode. For TE mode, the effective width W_{ev} of the basic mode $\psi_\nu(x)$ can be approximated as the effective width of the basic mode W_{e0}, $W_{e0} = W + \left(\frac{\lambda_0}{\pi}\right)\left(n_r^2 - n_c^2\right)^{-(1/2)}$, which can be obtained by bringing in the parameters, W_{e0} = 15.9414 μm, the beat length of the two lowest order modes, $L_\pi = \frac{\pi}{\beta_0 - \beta_1} \simeq \frac{4n_r W_{e0}^2}{3\lambda_0}$, L_π = 709.4386 μm. It is assumed that the incident field distribution at the front end of the multimode interference waveguide z = 0 is $\Psi(x, 0)$, and its field distribution is less than W_{e0}. In practical

FIGURE 7
Diagram of the field distribution in waveguide of a new tapered semiconductor laser.

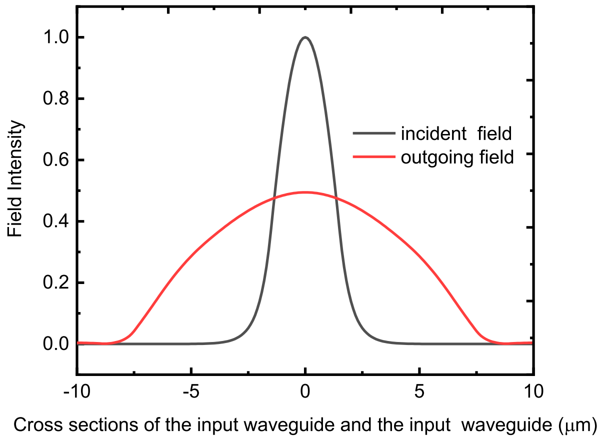

FIGURE 8
The incident field and the outgoing field of the input and output end of the new taper semiconductor laser waveguide.

applications, other radiation modes can be ignored, so $\Psi(x,0)$ can be expanded using the guided mode $\psi_{\nu}(x)$ in the waveguide, $\Psi(x,0) = \sum_{\nu=0}^{m-1} c_{\nu}\psi_{\nu}(x)$. If only the even-order symmetry mode is excited, the fundamental mode $\Psi(x,0)$ of the input waveguide will acquire a single image at $p(3L_{\pi}/4)$, where $p = 0,1,2,\cdots$ [15]. Taking p = 1, the multimode waveguide is monogram at L = 532.0789 μm.

In order to verify the theoretical calculation results, a symmetric 1 × 1 MMI with both input and output waveguide widths of 3 μm was simulated. Taking the theoretical length of the multimode interference waveguide as the reference, changing the length of the multimode interference waveguide, the simulation results are shown in Figure 2 The transmittance of 1 × 1 MMI will change accordingly, reaching the maximum at L = 538.1μm, which is 0.9829715. At this time, as shown in Figure 3, the fundamental mode of the input waveguide becomes a single image at L = 538.1 μm in the multimode interference waveguide, which is consistent with the theoretical value. The total waveguide length of the 1 × 1 MMI is 838.1 μm. The first and second order guided wave modes of the input waveguide cannot be imaged at L = 538.1 μm, and the energy entering the output waveguide is very small. Figure 4 shows the total field intensity of a region of 3 μm equal width to the input waveguide along the axis of 1 × 1 MMIZ, from which it can be seen that multiple modes of the multimode interference waveguide interfere with each other, forming different image points at different positions, and the energy of the input light field is redistributed. From the far-field distribution shown in Figure 5 below, it can be seen that the fundamental mode of the input waveguide excites the three guided wave modes of the output waveguide through the single image formed by the multi-mode interference waveguide, resulting in a bimodal far-field distribution of the 1 × 1 MMI semiconductor conductor laser with the waveguide structure mentioned above.

The taper angle θ of the tapered output waveguide greatly affects the output performance of the tapered semiconductor laser and is one of the key parameters of laser design. The size of the taper angle determines the area of the tapered output waveguide gain. When the diffraction distribution of the fundamental mode matches the tapered gain region, charge carriers can be effectively used to achieve high differential quantum efficiency of the fundamental mode [14] Therefore, in this paper, the output waveguide of the multi-mode interference coupler is changed from a straight waveguide to a tapered waveguide, and the width of the other end of the output tapered waveguide is set to 1 μm to ensure that the single-mode output has a stronger diffraction effect. The tapered output waveguide can have a larger taper angle, and the length of the multi-mode interference waveguide is re-optimized, and the length becomes 537.9 μm as shown as Figure 6, and the transmittance changes to 0.9785255. The transmittance decreased slightly. The field distribution in the new tapered semiconductor laser is shown in Figure 7, and the incident field and the outgoing field of the input and output end of the new taper semiconductor laser waveguide are intercepted, as shown in Figure 8, it can be seen that the field distribution in the waveguide expands with the increase of the waveguide width.

Compared with the conventional 1 × 1 MMI laser and the new tapered semiconductor laser, the far-field output characteristics of the laser are greatly improved, the full width at half maximum is reduced from 24.14° to 7.25°, and the far-field distribution changes from bimodal to unimodal, as shown in Figure 5. The simulation results show that the output waveguide of the multimode interference coupler changes from straight waveguide to tapered waveguide effectively to realize the conversion of different modes at both ends, and provides the seed light source of spatial single mode for the tapered output waveguide. Meanwhile, the tapered output waveguide also effectively reduces the optical power density of the output laser.

3 Conclusion

In order to increase the output power of the tapered semiconductor laser by increasing the volume of the gain medium while ensuring the single-mode output in the ridged waveguide region, a new tapered semiconductor laser with integrated multi-mode interference coupler is proposed and the design scheme is verified theoretically. During the simulation, it is found that by optimizing the waveguide structure and parameters of the multi-mode interference coupler, the spatial single-mode high-power seed source can be effectively provided for the tapered output waveguide. The tapered output waveguide is divided into two types: refractive index guidance and gain guidance. Because this paper is mainly to verify the feasibility of the design scheme, the structural parameters of the tapered output waveguide are not optimized. It is believed that through the collaborative optimization of the structure of the multi-mode interference coupler and the tapered output waveguide, this new type of tapered semiconductor laser with integrated multimode interference coupler can show more excellent performance.

In the process of designing the new type of tapered semiconductor laser, the design parameters in Ref. [10] are used in this paper, which are verified by the experimental results. At the same time, this paper fully considers the manufacturing process of the new tapered semiconductor laser to ensure that the processing difficulty of the new laser is comparable to that reported in the literature. Therefore, the processing of the new laser has a high feasibility.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JZ: Conceptualization, Data curation, Software, Supervision, Writing–original draft, Writing–review and editing. HS: Conceptualization, Data curation, Software, Writing–original draft. ZD: Software, Writing–original draft, Data curation, Validation. MY: Conceptualization, Software, Writing–original draft. PW: Conceptualization, Writing–original draft, Software. YZ: Conceptualization, Data curation, Writing–original draft. XF: Conceptualization, Data curation, Supervision, Writing–review and editing.

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Conflict of interest

Author YZ was employed by Shandong Tonye photoresist material technology CO., LTD.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. You D, Tan M, Chen W, Liu W. Effect of facet reflection on beam quality of tapered laser. *Chin J Lasers* (2023) 50(2):0201007. doi:10.3788/cjl220661

2. Abbasi SP, Mahdieh MH. Design of diode laser using slab coupled optical waveguide with graded refractive index structure. *Opt and Laser Technol* (2022) 147:107654. doi:10.1016/j.optlastec.2021.107654

3. Yuan M, Wang W, Wang X, Wang Y, Yang Q, Cheng D, et al. Demonstration of an external cavity semiconductor mode-locked laser. *Opt Lett* (2021) 46(19):4855–8. doi:10.1364/ol.428794

4. Li X, TaoShi BW, DongAdnan ML, Adnan M. Huitian *The influence of substrate tilt angle on the morphology of laser cladding layer*. *Surf and Coat Technol* (2020) 391:125706. doi:10.1016/j.surfcoat.2020.125706

5. Tan M, Dao-ming Y, Wen-tao G, Wei-hua L. Research progress of monolithic integration master-oscillation power-amplifiers. *Chin Opt* (2023) 16(1):61–75. doi:10.37188/co.2022-0022

6. Ni B, Luo C, Xu H, Dai Y, Qian Y, Shen Y, et al. Compact and low-crosstalk multimode waveguide crossing utilizing subwavelength holey metamaterial waveguides. *Opt Express* (2024) 32(20):35743–54. doi:10.1364/oe.533238

7. Song Z, Sun R, He F, Liu S, Ye X, Zhang J, et al. Phase-locked high-brightness interband cascade laser array with multimode interferometer couplers. *Opt Lett* (2024) 49(21):6197–200. doi:10.1364/ol.539389

8. Ghosh S, O'Callaghan J, Moynihan O, Huang D, Frish H, Rong H, et al. Scalable transfer printing approach to heterogeneous integration of InP lasers on silicon-on-insulator waveguide platform. *Appl Phys Lett* (2024) 125(8). doi:10.1063/5.0223167

9. Milbocker L, Desai D, Shu H, Cristobal E, Li G, Lyakh A. Design of high brightness tree-array quantum cascade lasers with broad area ridge waveguides and multimode interference couplers. *IEEE J Selected Top Quan Electron* (2025) 31(2):1–7. doi:10.1109/jstqe.2024.3404833

10. Gong Z, Yin R, Ji W, Wu C. Semiconductor laser using multimode interference principle. *Opt and Laser Technol* (2018) 98:75–8. doi:10.1016/j.optlastec.2017.06.029

11. Zang Z, Minato T, Navaretti P, Hinokuma Y, Hamamoto K. High-power (>110 mW) superluminescent diodes by using active multimode interferometer. *IEEE Photon Technol Lett* (2010) 22(10):721–3. doi:10.1109/LPT.2010.2044994

12. Gong Z, Shunchao Y, Yonggang Z, Yingtian X, Jie F. Double trapezoidal multimode interference coupler used to improve Electro-Optical efficiency of semiconductor laser. *Chin J Lasers* (2024) 51(14):1401011. doi:10.3788/cjl240559

13. Chen Z, Qu HW, Ma XL, Qi AY, Zhou XY, Wang YF, et al. High-brightness low-divergence tapered lasers with a narrow taper angle. *Chin Phys Lett* (2019) 36(8):084201. doi:10.1088/0256-307x/36/8/084201

14. Yang J. *Study on mode regulation of tapered laser diode*. Changchun: Changchun University of Science and Technology (2023).

15. Soldano LB, Pennings ECM. Optical multi-mode interference devices based on self-imaging: principles and applications. *J Lightwave Technol* (1995) 13(4):615–27. doi:10.1109/50.372474