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Design of high power pump source of eye safe laser for geo-scientific application

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The design consideration of high power diode laser at wavelength of 980 nm as pump source for erbium doped glass eye safe laser at wavelength 1.54 μm is presented here. The design of high power laser requires precise control of waveguide dimensions, material and doping profile of layers. The maximum optical power is proportional to transverse optical spot size. The transverse optical spot size and threshold current density have been calculated with transverse waveguide thickness. The effect of current spreading on threshold current density is calculated. The geo-scientific application of eye safe laser is also presented.

Keywords: Diode laser, High power pump source, Eye safe laser

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1 Introduction

The eye safe lasers are showing greater attention over other lasers for the study of environmental changes, laser range finder, and other applications. Radiations shorter than 400 nm and longer than 1400 nm are strongly absorbed by tissues so they do not penetrate the eye inside and do not cause retina damage. A wavelength of 1.54 μm is considered as a safe one for direct looking at the radiation beam of energy density a hundred times higher than for 10.6 μm (CO_2 laser) and 2×10^5 times higher than for wavelength of 1.06 μm (Nd:YAG laser). Erbium-doped optical glasses are effective media for active lasers generating eye safe radiation of a wavelength 1.54 μm. There has been a great interest in high-power diode laser operating at wavelength around 980 nm, because of its important applications as pump sources for Er-doped optical glass laser (eye safe laser) and Er-doped optical fiber amplifiers (EDFA), generators of blue light via frequency doubling, medical therapy, material processing, and soldering.

For all active atmospheric remote sensors, eye-safety is an absolute requirement. In the first laser systems generating eye safe radiation, a Raman shifter was used in the form of a methane cell in which a conversion of radiation, generated by YAG:Nd^{3+} (λ=1064 nm), into radiation of wavelength of 1.54 μm occurred. Because the efficiency of this process is not high, these systems have not found practical applications[1]. Erbium laser glasses have attracted much attention due to their capability for emission at the eye-safe wavelengths and optical communication windows of 1.54 μm [Ref. 2]. Eye-Safe Er: Glass lasers are readily tunable in the atmosphere's high transmission window between 1535 nm and 1565 nm. Again, Eye-Safe 1.54 μm lasers are the way to go since detector arrays are readily available in this region. The application of eye safe laser LIDAR (light detection and ranging) lies in wide range. Laser Ranging includes: robotics, 2-D and 3-D machine vision; collision avoidance for all kinds of traffic control; long range target tracking and satellite laser ranging; laser polarimetry, vibrometry, dynamics, and microdynamics measurements; topographic mapping and bathymetry systems.

2 Design Consideration of High Power Laser

The InGaAs/GaAs material is used for the realization of lasers at wavelength 980 nm. The high band gap and low refractive index AlGaAs or InGaAsP material lattice matched to GaAs is used for the transverse confinement of carrier as well as light. The effect of indium mole fraction and quantum well (QW) thickness on emission wavelength and threshold current density, effect of linearly graded thickness on optical confinement, and effect of number of QWs and cavity length on threshold current density have been calculated and presented elsewhere[3]. Here, we present design consideration of waveguide thickness for obtaining high maximum power from laser. The effect of lateral current spreading on threshold current density has also been calculated.

2.1 Effect of waveguide thickness

The continuous wave (CW) power of a diode laser is generally limited by either thermal rollover or catastrophic optical mirror damage (COMD). Thermally limited power saturation can be eliminated by designing laser structure to have high total power conversion efficiencies, low threshold current density and weak temperature sensitivity for both threshold current and the external differential quantum efficiency[4]. From the definition of internal optical power density at COMD, P_{COMD} , the maximum CW output power is given by

$$P_{max,CW} = (d/\Gamma)w[(1-R)/(1+R)]P_{COMD} \quad \ldots (1)$$

where, w is the strip width and R is front facet power reflectivity. It has been established that for conventionally facet-passivated diodes, P_{COMD} is a function of active region material, being in effect inversely proportional[5] to the surface recombination velocity as long as $s \geq 10^5$ cm/s. That is, for a given active region material with $s \geq 10^5$ cm/s and given strip width $P_{max,CW}$ directly scales with transverse spot size d/Γ [d is quantum well(s) thickness and Γ the (transverse) optical confinement factor]. The subsequent decrease in the (transverse) optical confinement, Γ can be offset by increasing the device cavity length, L, in structure of low internal loss α_I (< 2 cm^{-1})[6]. Thus, larger optical spot size can be obtained with little penalty in threshold current density or efficiency. A schematic representation of the broad waveguide separate confinement heterostructure (BW-SCH) is shown in Fig. 1. The QW is 8 nm $In_{0.20}Ga_{0.80}As$ between $Al_{0.2}Ga_{0.8}As$ waveguide and $Al_{0.50}Ga_{0.50}As$ clad layers. The layers above and below QW are p-type and n-type, respectively. The doping of waveguide is low (2-7×10^{17} cm^{-3}) for low optical loss and doping concentration increases from clad region to highly doped p^+-GaAs (2×10^{19} cm^{-3}) cap layer for decrease of ohmic resistance.

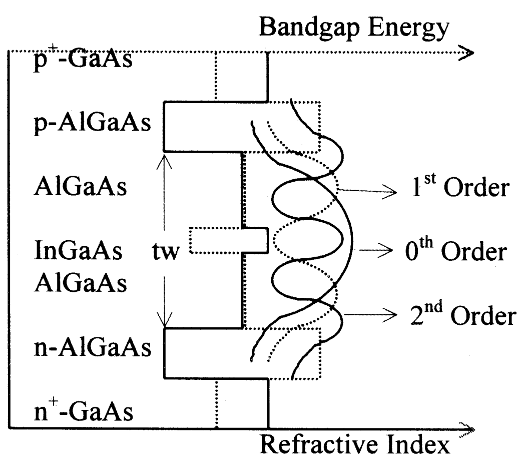

Fig. 1—Schematic of transverse waveguide refractive index profile and Bandgap energy diagram of QW laser with optical intensity of first three modes

Since QWs are very narrow (8 nm) compared to the waveguide thickness, it can be ignored for solving optical field. The optical confinement factor is evaluated using well-known solutions of optical field in slab waveguide.

Basic properties of laser diode vary according to the change of d/Γ. The threshold current density is proportional to d/Γ as shown in Fig. 2. The procedure for calculation of threshold current density has been explained elsewhere[3]. For high power lasers, it is necessary to design laser waveguide for large value of d/Γ, as shown in Fig. 2, the increase of d/Γ up to twice (at 2nd order mode cutoff) of its minimum value only increases the threshold current density up to 13%. For tw < 0.25 μm, threshold current increases sharply with decrease of waveguide thickness due to increase of clad loss. So, choice of waveguide thickness for large value of d/Γ is limited by number of optical modes as threshold current density and optical beam width both increase rapidly with increase of number of excited modes. The optical confinement in QW for 1st order mode is so small that it cannot reach lasing threshold. So, we can choose waveguide thickness below cutoff

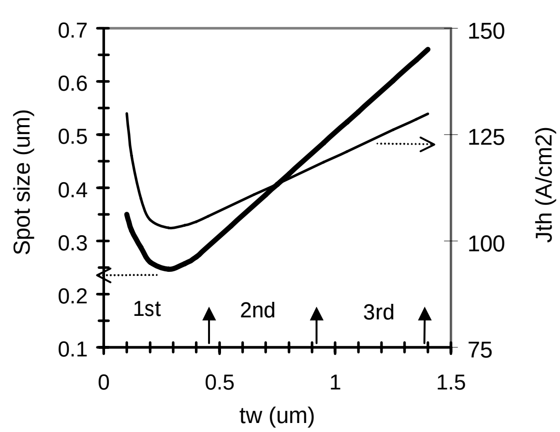

Fig. 2—The variation of transverse spot size, d/Γ, and threshold current density with transverse waveguide thickness

of 2^{nd} order mode. As shown in Fig. 1, the proper design of cladding region thickness is such that it does not disturb fundamental mode but a considerable amount of power of second order mode lies in highly doped region above cladding region. The photons in highly doped region are absorbed and so internal loss of cavity for 2^{nd} order mode becomes so high that either it does not lase or lase at high drive current level with very low power content. This provides chance to further increase of waveguide thickness (i.e. d/Γ) above cutoff of 2^{nd} order mode. Further, applying non-absorbing mirror, such as ZnSe [Ref. 7] on oxide free facets should eliminate COMD and allow CW operation above 10 W.

The external differential quantum efficiency of laser is expressed as

$$\eta_d = \eta_i\,[\alpha_m/(\alpha_i+\alpha_m)];\ \ \alpha_m = (1/2L)\ln(1/R_1R_2)$$

where, η_i is the internal efficiency, α_m and α_i are mirror and internal cavity losses, respectively, L is cavity length, R_1 and R_2 are mirror reflectivity. Relatively low doping levels of $5\text{-}7\times10^{17}$ cm^{-3} in AlGaAs cladding layers might contribute to lower free carrier absorption and does not contribute to internal loss for fundamental optical mode[8]. Internal loss is proportional to number of QWs possibly due to scattering at QW and barrier interfaces. Increase of waveguide thickness decreases overlapping with cladding region and also with QW, both of these contribute to lower internal loss and hence external differential quantum efficiency increases with increase of waveguide thickness. The increasing waveguide thickness reduces peak optical power density at facet hence decreasing the self-absorption of laser light by QW near the facet, which decreases the facet temperature. However, increase in waveguide thickness increases threshold current and the carrier leakage, which results in higher non-radiative recombination, which increases temperature. The increase of temperature decreases η_d. These opposite factors give an optimum waveguide thickness with lowest degradation rate. The optical confinement for narrow waveguide (2-10 μm) laser depends on both waveguide thickness and width and can be calculated after solving electromagnetic equations in self-consistence manner. The threshold current in narrow waveguide laser also greatly depends on lateral current spreading.

2.2 Material consideration

The trend in high power and reliable InGaAs/AlGaAs/GaAs lasers replaces AlGaAs by InGaAsP. The growth of InGaAsP alloys lattice matched to GaAs substrate is very attractive as an aluminium free alternative to the conventional AlGaAs based materials. The aluminium free InGaAs(P)/ InGaP/GaAs material system has several advantages over the GaAs/AlGaAs material system for the realizaion of reliable, high power diode lasers: (1) the low reactivity of InGaP to oxygen facilitates regrowth for the fabrication of single mode index guided structure[9], (2) higher electrical[10] and thermal conductivity[11] compared with AlGaAs, (3) potential for improved reliability[12] and (4) potential for growth of reliable diode lasers on Si substrtates[13]. Aluminium free material for active region offers lower surface recombination velocity and material reliability leads to higher catastrophic optical mirror damage power P_{COMD} and higher reliability. Higher electrical and thermal conductivity result in higher power conversion efficiency. The use of InGaAsP active region enables strained QW and strain compensated active region for a wide range of wavelength 0.7- 1.1 μm. The use of high bandgap material such as AlGaAs and AlGaInP for waveguide and clad layer is important (necessarily for large waveguide thickness devices) for reducing electron leakage from the active region, which results in lower temperature sensitivity and the reduction of thermal rollover at high power. The power for COMD in AlGaAs and InGaAsP is about equal (~15 MW/cm^2) and also does not vary with increase of transverse spot size d/Γ. The long-term reliability of InGaAsP based lasers may be high due to its low oxidation rate.

2.3 Effect of lateral current spreading

The lateral current spreading occurs in semiconductor lasers when current has no lateral confinement. In this case, current has component parallel to the layers, which depends on the electrical conductivities inside the structure. Wide area lasers are used for high power application and at the same time high power narrow area lasers are also very useful for other applications. The lateral current spreading becomes more pronounced as strip width decreases. Ridge waveguide structure is used for lateral confinement of current and optical field in lasers. To avoid surface recombination the etch depth never reaches the active region.

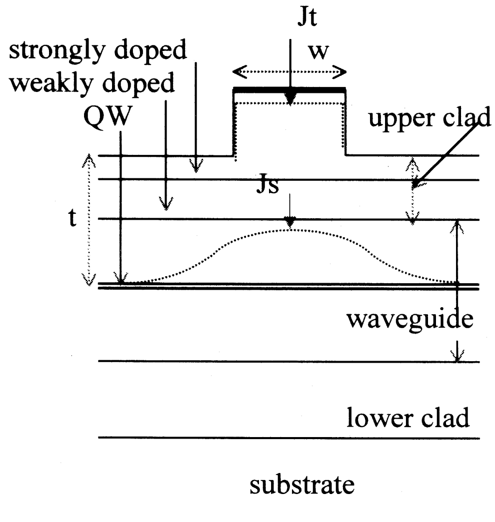

Fig. 3—Schematic diagram of ridge waveguide structure showing lateral current spreading

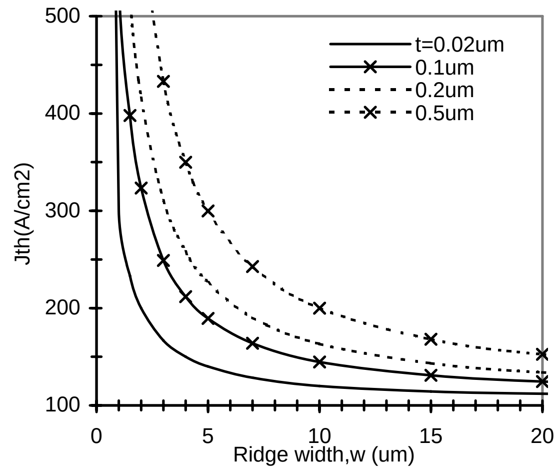

Fig. 4—The effect of current spreading on threshold current density with ridge width for different residual waveguide thickness

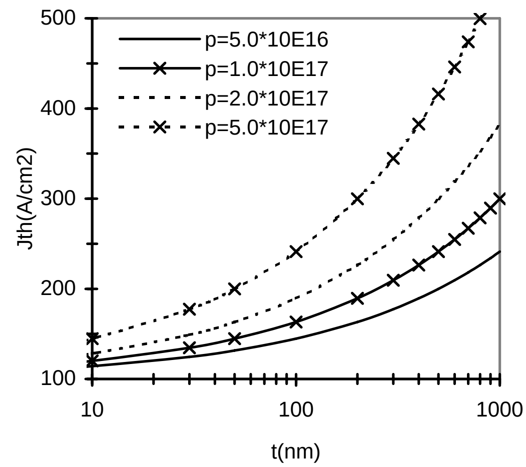

Fig. 5—Threshold current density variation with residual waveguide thickness at different doping concentrations

A major requirement to achieve long lifetimes is the exact control of the waveguide geometry and layer composition as well as the doping profile. These may affect the threshold current and series resistance and therefore, also the operating temperature of the device. We present here the influence of the doping and residual waveguide thickness on threshold current. Figure 3 shows ridge waveguide structure for lateral current as well as optical confinement.

The lateral current spreading in ridge waveguide structure including carrier diffusion as well as non-radiative recombination[14] is given by[15]

$$J(x)=Js\,\{1+(|x|-w/2)/ls\}^{-2} \quad \text{for } |x|>w/2$$

$$J(x)=Js \quad \text{for } |x|<w/2$$

where Js is current density in active region after spreading under strip and given in term of total injected current density, Jt and effective spreading width w_{eff} [Ref. 16] by

$$Jt = Js \cdot w_{eff}/w; \quad w_{eff} = w\,(1+2\sqrt{2}ls)$$

ls is current spreading width given by $ls = (k \cdot T \cdot \sigma \cdot t/e \cdot Js)^{1/2}$; k the Boltzmann constant, T temperature, e elementary charge, t residual waveguide thickness, and σ is conductivity of current spreading layer calculated by $\sigma = e \cdot \mu \cdot p$ (μ is mobility of holes taken to be 130 cm^2/Vs for AlGaAs layer, and p is average p-doping concentration over thickness, t).

The effect of current spreading on threshold current is shown in Fig. 4 for average p-doping of 1.6×10^{17} cm^{-3} and hole mobility of 130 $cm^2/V \cdot s$ [Refs 17-19]. The current spreading affects seriously the laser threshold current density for ridge width below 5 μm. Figure 5 shows variation of threshold current density of 5 μm ridge width at different average doping concentrations. It is important to control residual waveguide thickness precisely during etching. The doping concentration should be low for suppressing current spreading. In narrow area lasers excitation of first order lateral mode due to lateral current

Table 1—Comparison of calculated (bold) and experimental [Ref. 21] values of threshold current density including lateral current spreading effect

w (μm)	L = 400μm Cal. Exp.	L = 500 μm Cal. Exp.	L = 750 μm Cal. Exp.	L = 1000 μm Cal. Exp.	L = 1500 μm Cal. Exp.	L =2000 μm Cal. Exp.
2			**645**			
			700			
2.5	**350**					
	310					
2.7		**360**		**326**	**311**	**307**
		374		296	296	296
10		**191**		**170**	**160**	**158**
		196		180	160	160
15		**171**		**151**	**142**	**140**
		173		146	142	140
50		**142**				
		136				

spreading increases threshold largely and so etching of highly doped layer above waveguide region becomes necessary to avoid this problem.

Table1 gives the comparison of calculated and experimental data for different ridge widths (*w*) and cavity lengths (*L*) including effect of lateral current spreading. The calculated values are in good agreement with experimental values.

3 Conclusion

The design of high power laser requires precise control of waveguide dimensions, material and doping profile of layers. The increase of waveguide thickness below cutoff of second order transverse mode doubles spot size and hence maximum optical power with increase of threshold current density only of 13%. The unconverted energy at 980 nm will be extremely low and not threatening to eye safety. The lateral current and optical confinement become important for lasers having narrow strip width. The effect of current spreading on threshold current density with ridge waveguide dimensions is calculated. The threshold current depends greatly on residual waveguide thickness and doping concentration.

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