Vol 10 No 7, July 2001
1009-1963/2001/10(07)/0621-05
Chinese Physics
© 2001 Chin. Phys. Soc.
and IOP Publishing Ltd

DESIGN OF A 532nm Nd:YVO_4/KTP SINGLE-FREQUENCY LASER*

Xu Chun-lin(徐春林)[a)†], Shen Nai-cheng(沈乃澂)[b)], Zang Er-jun(臧二军)[b)],
Sun Yi-min(孙义民)[b)], Lu Hai-ning(鲁海宁)[b)],
Zhao Kun(赵 昆)[b)], and Zhang Xue-bin(张学斌)[b)]

[a)] *Institute of Microelectronics, Tsinghua University, Beijing* 100084, *China*

[b)] *The Joint Laboratory of Advanced Technology in Measurements, Beijing* 100013, *China*

(Received 8 October 2000; revised manuscript received 21 March 2001)

A model of the laser-diode pumped solid-state laser is developed to deduce the minimum average radii of the pump beam in the solid medium, since the smaller the cavity waist, the higher the laser output power is expected to be. With an appropriate coupling system consisting of the collimating lens, prism pair and focusing lens, a diode-pumped single-frequency Nd:YVO_4/KTP intracavity frequency-doubling cw laser has been demonstrated through the precise temperature control of the Nd:YVO_4 crystal, the KTP crystal and the diode laser. The 532nm single-frequency output power of 40.4mW (in fact 55mW if the reflection loss of the triangular prism is taken into account) is obtained for an incident power of 515mW. It is derived theoretically and is verified in experiment that the frequency drift of the free-running laser can be reduced by increasing the cavity length.

Keywords: 532nm laser, single frequency, Nd:YVO_4, KTP
PACC: 4255

I. INTRODUCTION

Diode lasers are attractive as pumps due to their compactness, high efficiency, reliability, low price and low noise. The power conversion efficiency depends strongly on the overlap of the pump and the resonator beams. Diode lasers have different divergence and extension in the directions parallel and perpendicular to the junction. To obtain high overlap and efficiency, a coupling optics is necessary. A widely-used optics consists of a collimating lens, prism pair and a focusing lens.[1−2]

We calculate the minimum average spot radii of the pump beam in the medium from the beam propagation equations of the laser diode. By making use of an appropriate coupling optics to keep the average spot radii of the pump beam nearly to the minimum, we obtained low threshold and high efficiency in a LD pumped Nd:YVO_4/KTP single-frequency laser.

II. THEORY

Diode-pumped solid-state lasers have developed rapidly in the last 15 years.[3,4] Neodymium-doped yttrium orthovanadate(Nd:YVO_4) is a birefringent laser material with a high absorption cross section and a high gain as compared to Nd:YAG. Fan and Byer[5] have developed rate equation models for cw end-pumped four-level Nd^{3+} lasers and obtained the threshold:

$$P_{\mathrm{a,th}} = \frac{\pi h\nu_{\mathrm{p}}}{4\sigma_{\mathrm{e}}\eta_{\mathrm{p}}\tau}(w_0^2 + \omega_{\mathrm{p}}^2)\delta, \qquad (1)$$

where $P_{\mathrm{a,th}}$ is the absorbed pump power at the threshold, ν_{p} is the pump photon frequency, η_{p} is the pump quantum efficiency which is the number of ions in the upper manifold created by one absorbed photon, w_{p} and w_0 are the waist radii of the pump laser and laser cavity mode respectively, and δ is the round-trip loss. The minimum average values of w_0^2 and w_{p}^2 are inversely proportional to the absorption coefficient (α) of the laser medium.[5] Thus the threshold is inversely proportional to the quantity $\sigma_{\mathrm{e}}\alpha\tau$. The characteristics of four laser mediums at 1064nm are shown in table 1.

The 3at% Nd:YVO_4 has the smallest value of quantity $1/(\sigma_{\mathrm{e}}\alpha\tau)$. Its absorption coefficient (α) is the largest. The single-frequency operation can be due to its short absorption depth (90μm)[7] so that the number of optical elements in the cavity is the least. Except for the Nd:YVO_4 and the KTP, the laser does not need any other element to choose a single longitudinal mode, thus the cavity loss (δ) of the 3at% Nd:YVO_4 laser is the smallest, and the minimum average values of w_0^2 and w_{p}^2 the smallest for its largest absorption

*Project supported by State Key Laboratory on Integrated Optoelectronics.
†E-mail: xuchunlin@263.net

Table 1. The characteristics of four laser mediums at 1064nm.

Laser medium	Nd^{3+} density /at%	Absorption coefficient /cm^{-1}	Fluorescent lifetime $\tau/\mu s$	σ_e /$10^{-19}cm^2$	$1/(\alpha\sigma_e\tau)$ /$s^{-1}cm^{-1}$
Nd:YAG	1.1	7.1[6]	240[8]	4.6 [8]	1.28×10^{21}
a-cut	1.1	28.8[6]	98[8]	12.20 [8]	2.9×10^{20}
Nd:YVO_4	2.02	72.4[6]	74[8]	12.22[8]	1.53×10^{20}
π polarization	3	111[7]	57[8]	12.27[8]	1.24×10^{20}

coefficient (α). The intracavity second-harmonic generation coefficient is the largest because it is inversely proportional to w_0^2. Thus the threshold is the smallest and the 3at% Nd:YVO_4 turns out to be the most suitable laser medium for a single-frequency laser in a standing cavity at 1064nm.

An AlGaAs laser diode with a $1\mu m\times100\mu m$ emitting aperture and 29.5° (perpendicular to the junction), 5.9° (parallel to the junction) divergence is used as the pumping source. Its centre wavelength is temperature-tuned to the absorption line of the Nd:YVO_4 crystal at 809nm. The coupling system consists of a collimating lens (f_1), prism pair and a focus lens (f_2) as shown in Fig.1. A schematic diagram of the pump beam and laser mode in the gain medium is shown in Fig.2.

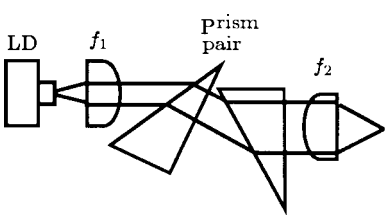


Fig.1. A schematic diagram of the collimating lens-prism pair-focusing lens pumping system.

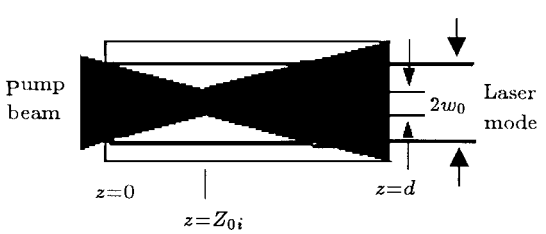


Fig.2. A schematic diagram of the pump beam and laser mode in the gain medium.

The propagation equations of the elliptic Gaussian beam of the laser diode are:[9]

$$w_{px}^2(z) = w_{x0}^2\{1 + [\lambda z/(\pi w_{x0}^2)]^2\} \quad (2)$$

$$\text{and } w_{py}^2(z) = \{w_{y0} + w_{e0}[1 + \lambda^2 z^2/(\pi w_{e0}^2)^2]^{1/2}\}^2, \quad (3)$$

where λ=0.809μm, $w_{x0} = \lambda/(\pi\theta_x) = 0.809/(\pi \times 29.5\pi/180) = 0.5\mu m$,[10] $w_{e0} = \lambda/(\pi\theta_y)$=$0.809/(\pi \times 5.9\pi/180) = 2.5\mu m$,[10] w_{y0}=50−w_{e0}=47.5μm.

According to the Lagrange invariant,[11] the quantity ($h\ n\ u$) remains constant as a beam passes through an linear optical system. In propagating through the coupling system, the propagation equations of the laser diode beam become:

$$w_{px}^2(z) = (0.5M_x)^2\left\{1 + \left[\frac{0.809(z - z_{0x})}{\pi(0.5M_x)^2}\right]^2\right\} \quad (4)$$

$$\text{and } w_{py}^2(z) = \left\{47.5M_y + 2.5M_y \cdot \left\{1 + \frac{0.809^2(z - z_{0y})^2}{[\pi(2.5M_y)^2]^2}\right\}^{1/2}\right\}^2. \quad (5)$$

The magnification of the optical coupling system in the plane perpendicular and parallel to the junction are M_x and M_y, respectively. The optics waist radii of the elliptic Gaussian beam are changed from w_{x0} to $M_x w_{x0}$ in the x-direction and from $(w_{y0} + w_{e0})$ to $M_y(w_{y0} + w_{e0})$ in the y-direction. The divergences of the elliptic Gaussian beam are changed from $\lambda/(\pi w_{x0})$ to $\lambda/(\pi M_x w_{x0})$ in the x-direction and from $\lambda/(\pi(w_{y0} + w_{eo}))$ to $\lambda/(\pi M_y(w_{y0} + w_{e0}))$ in the y-direction. The product of the beam waist and its divergence is constant (Lagrange invariant) in the x- or y-directions. After the elliptic Gaussian beam is incident into the medium with the refractive index n (n=2.165 for Nd:YVO_4[12]), the beam propagation equations[13] are:

$$w_{px}^2(z) = (0.5M_x)^2\left\{1 + \left[\frac{0.809(z - z_{0x})}{n\pi(0.5M_x)^2}\right]^2\right\} \quad (6)$$

$$\text{and } w_{py}^2(z) = \left\{47.5M_y + 2.5M_y \cdot \left\{1 + \frac{0.809^2(z - z_{0y})^2}{[\pi n(2.5M_y)^2]^2}\right\}^{1/2}\right\}^2. \quad (7)$$

A gain medium of length d is end-pumped by a laser diode. The pump radiation is absorbed exponentially in the gain medium when it propagates along the z-axis, and the intensity decreases according to[14]

$$I_{\rm p}(z) = I_{\rm p}(0)\exp(-\alpha z), \tag{8}$$

where z is the distance to the front mirror and α is the absorption coefficient at the pumping wavelength (809nm).

The weighted average of the radii of the elliptic Gaussian beam in the medium is:[9]

$$w_{{\rm p}i} = \left[\int_0^d w_{{\rm p}i}^2(z)\exp(-\alpha z){\rm d}z \Big/ \int_0^d \exp(-\alpha z){\rm d}z\right]^{1/2}, \tag{9}$$

where $i = x$ or $y, \alpha = 0.0111\mu{\rm m}^{-1}$, d=500μm. We can calculate the values of $w_{{\rm p}x}$ and $w_{{\rm p}y}$ from Eqs.(6)–(9), as shown in Figs.3 and 4. When M_x=6.3 and Z_{0x}=85μm, the minimum of $w_{{\rm p}x}$ is 4.5μm. When M_y=0.29 and Z_{0y}=75μm, the minimum of $w_{{\rm p}y}$ is 25.8μm.

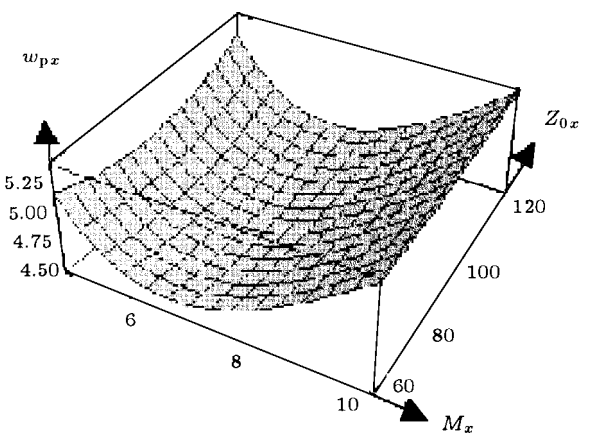


Fig.3. $w_{{\rm p}x}$ as a function of M_x and Z_{0x}. M_x is the magnification of the optical coupling system in the plane perpendicular to the junction of the laser diode. Z_{0x} is the distance from the front end of Nd:YVO_4 to the waist of pumping beam in the plane perpendicular to the junction.

In the coupling system shown in Fig.1, f_1 is the 3mm focal length collimating lens, f_2 is the 3mm focal length focusing lens, and the expansion ratio of the prism pair is three in the plane parallel to the junction. Thus M_x=1 and M_y=1/3. When Z_{0x}=Z_{0y}=75μm, $w_{{\rm p}x}$=20.3μm and $w_{{\rm p}y}$=26.1μm are calculated from Eqs.(6)–(9).

The resonance frequency in the standing cavity is given by:

$$\nu = qc/(2n_1L_1 + 2n_2L_2 + 2n_3L_3), \tag{10}$$

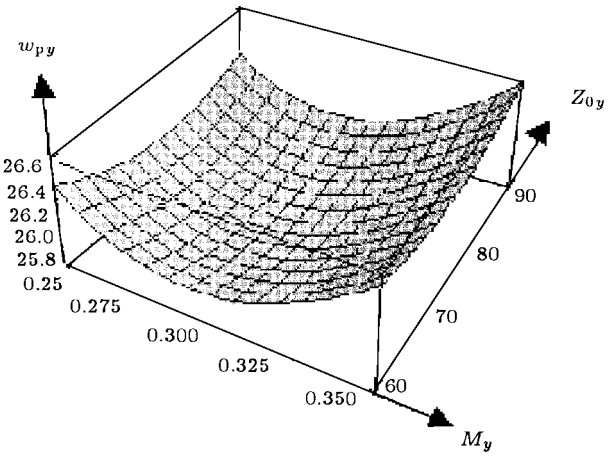


Fig.4. $w_{{\rm p}y}$ as a function of M_y and Z_{0y}. M_y is the magnification of the optical coupling system in the junction plane. Z_{0y} is the distance from the waist of pumping beam to the front end of Nd:YVO_4 in the junction plane.

where q is an integer, c is the speed of light in vacuum, $2L$=$2(n_1L_1 + n_2L_2 + n_3L_3)$ is the optical round-trip path length of the resonator cavity, n_1, n_2 and n_3 are the refractive indices of the Nd:YVO_4 crystal, the KTP crystal and the air, respectively. L_1, L_2 and L_3 are the physical length of the Nd:YVO_4 crystal, the KTP crystal and the air in the cavity, respectively. From Eq.(10) it is seen that the change of resonance frequency with temperature T is given by

$$\frac{\partial\nu}{\partial T} = -\frac{\nu}{n_1L_1 + n_2L_2 + n_3L_3} \cdot \left[n_1\frac{\partial L_1}{\partial T} + L_1\frac{\partial n_1}{\partial T} + n_2\frac{\partial L_2}{\partial T} + L_2\frac{\partial n_2}{\partial T} + n_3L_3\left(\frac{1}{L_3}\frac{\partial L_3}{\partial T} + \frac{1}{n_3}\frac{\partial n_3}{\partial T}\right)\right], \tag{11}$$

where $(1/L_3)(\partial L_3/\partial T)$ is the thermal expansion coefficient of the invar bracket. In standard atmosphere state, $(1/n_3)(\partial n_3/\partial T)$=$-9.3\times10^{-7}/^\circ$C,[15] $(1/L_3)(\partial L_3/\partial T)$=$9\times10^{-7}/^\circ$C,[16] $\partial n_1/\partial T$=$3.0\times10^{-6}/^\circ$C,[17] $\alpha_1 = (1/L_1)(\partial L_1/\partial T) = 4.43\times10^{-6}/^\circ$C,[17] $(\partial n_2/\partial T) \le 1.45\times10^{-5}/^\circ$C,[18] $(1/L_2)(\partial L_2/\partial T) \le 1.1\times10^{-5}/^\circ$C,[18] and

$$\Delta\nu \le \frac{\nu}{n_1L_1 + n_2L_2 + n_3L_3} \cdot [6.3\times10^{-6}\Delta T_1 + 1.72\times10^{-4}\Delta T_2 + 3\times10^{-8}n_3L_3\Delta T_3], \tag{12}$$

where the unit of L is mm, ΔT_1, ΔT_2 and ΔT_3 are the temperature change of Nd:YVO_4, KTP and

the air in the cavity. When L=100mm, ΔT_1=0.3°C, ΔT_2=0.06°C and ΔT_3=1.5°C, $\Delta\nu \leq$94.2MHz.

Ⅲ. EXPERIMENTS

Figure 5 shows a schematic diagram of the Nd:YVO_4/KTP single-frequency laser. A 1 W laser diode is used as the pumping source. The beam of the LD is collimated, then it is expanded in the plane parallel to the junction by the prism pair (the expansion ratio being three), and is focused at last into a 0.5mm thick 3at% Nd:YVO_4. The input facet is coated with a reflectivity of 93% at 532nm, 99.7% at 1064nm, 5% at 809nm. A 5mm thick KTP is put into the cavity and is used for type II phase matching. The other facet of the Nd:YVO_4 crystal and the two facets of the KTP crystal are coated with a reflectivity of less than 0.3% at 1064nm. The Nd:YVO_4 and the KTP crystals are separately temperature-controlled with an accuracy better than ±0.01°C in order to maintain the 1.064μm laser polarization parallel to the c-axis of the Nd:YVO_4 crystal.[6]

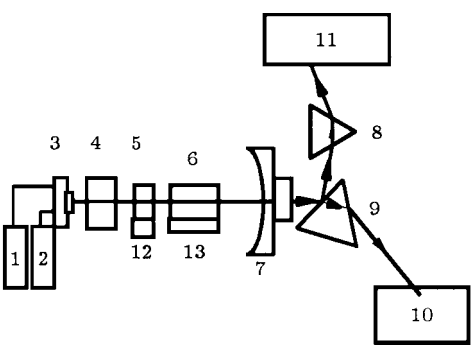


Fig.5. A schematic diagram of a LD pumped Nd:YVO_4/KTP laser: 1, power supply; 2, 12 and 13, temperature controller; 3, LD; 4, optical coupling system; 5, Nd:YVO_4; 6, KTP; 7, output mirror; 8 and 9, triangular prism; 10, power meter; 11, scanning Fabry–Pérot interferometer.

A concave mirror with a 100mm radius of curvature and reflectivity of 99.7% at 1064nm and 5% at 532nm is used as the output mirror. The effective length of the cavity is about 100mm. The output lasers are separated by a triangular prism (9). The reflected light from the prism (9) is separated by another triangular prism (8). The optical spectrum is monitored at 532nm with a scanning Fabry–Pérot interferometer of a 9GHz free spectral range, as shown in Fig.6. The output power is measured by a power meter. The threshold power of the laser is 5mW. Behind the prism (9), the stable laser output powers of 40.4mW at 532nm and 12mW at 1064nm are obtained for a pump power of 515mW. In front of the prism (9), the total output power of the 532nm and 1064nm lasers is 74.4mW. Figure 7 shows the output power of the 532nm laser behind the prism (9) and the total power of the 532nm and 1064nm lasers in front of the prism (9) versus the LD pump power. The conversion

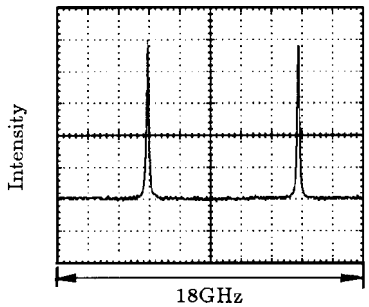


Fig.6. The optical spectrum of a 532nm single-mode laser measured by using a scanning interferometer with 225 MHz resolution and a 9 GHz free spectral range.

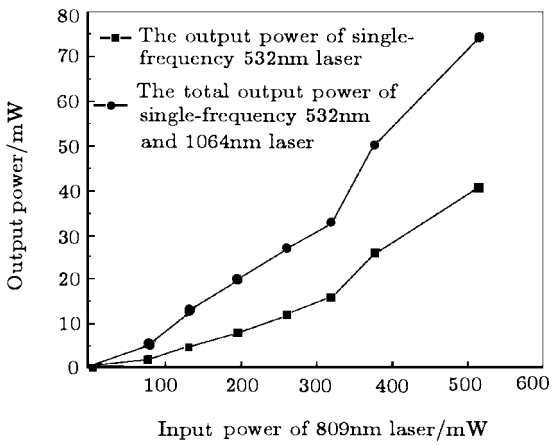


Fig.7. The 532nm single-frequency output power and the total output power of single-frequency 532nm and 1064nm lasers versus pump power.

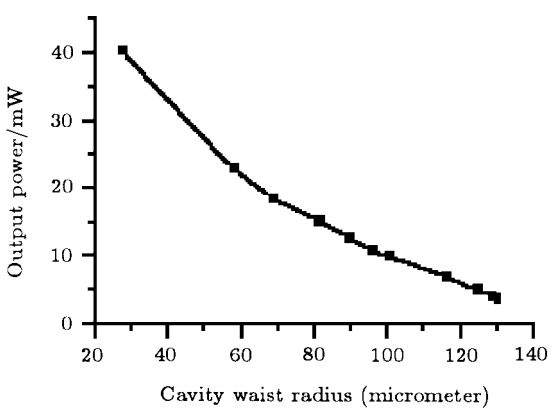


Fig.8. The output power of the 532nm laser behind the prism (9) versus the cavity waist radius.

efficiency (10.7%) of the laser at 532nm is much higher than that (2.6%) quoted in Ref.[6] since the focusing spot size of the pumping diode laser in Ref.[6] is larger ($230\mu m \times 100\mu m$). Figure 8 shows the output power of the 532nm laser behind the prism (9) versus the cavity waist radius when the pump power is 515mW. The smaller the cavity waist, the higher the output power.

Table 2 gives the frequency shift versus the cavity length observed with a scanning Fabry–Pérot interferometer when Nd:YVO_4 is controlled at 30°C and the pumping power is 376mW. This shows a fairly good agreement with the theoretical prediction that the frequency drift is decreased by an increase in the cavity length.

Table 2. The frequency shift versus the cavity length.

L/mm	$\Delta\nu$/GHz
100	0.1
50	0.2
20	0.5

When Nd:YVO_4 and KTP crystals are respectively controlled at 30°C and 25°C, and the output power of the 532nm laser is 15mW, the free-running laser can be stable at the spectrum of I_2 at 532.195nm for 1 h. Hyperfine spectra of $^{127}I_2$ near 532nm have been studied via modulation transfer spectroscopy.[19]

IV. CONCLUSION

In conclusion, from the equation of the laser threshold and the second-harmonic generation coefficient, the 3at% Nd:YVO_4 proves to be the most suitable laser medium for a single-frequency laser in a standing cavity at $1.064\mu m$. We calculate the minimum average spot radii of the pump beam in the medium from the beam propagation equations of the laser diode, and use an appropriate coupling optics to make the average spot radii of the pump beam nearly the minimum. The 532nm single-frequency output power of 40.4mW (in fact 55mW if the reflection loss of the triangular prism (9) is taken into account) is obtained for an incident power of 515mW.

The Nd:YVO_4/KTP laser runs in the single frequency because of the short absorption depth of Nd:YVO_4 [7] and the phase-retardation (λ or $\lambda/2$) plate of KTP.[6] Its optic–optic efficiency is not the highest because of the low incident power (515mW), short fluorescent lifetime ($57\mu s$[8]) of Nd:YVO_4 and the common quality of the coating of Nd:YVO_4, KTP and the output mirror. If the reflection of the output mirror at 1064nm is more than 99.9%, the laser easily runs in two longitudinal modes.

ACKNOWLEDGMENTS

We thank Professor Wang Chu of Peking University and Professor Huo Yu-jing of Tsinghua University for their help.

References

[1] Berger J, Welch D F, Scifres D R, Streifert W and Cross P S 1987 *Appl. Phys. Lett.* **51** 1212
[2] Berger J, Welch D F, Scifres D R, Wtreifert S and Cross P S 1987 *Electron. Lett.* **23** 669
[3] He J L, LU X Q and Jia Y L *et al* 2000 *Acta Phys. Sin.* **49** 2106 (in Chinese)
[4] Zhang H L, He J L and Chen Y C *et al* 1998 *Acta Phys. Sin.* **47** 1579 (in Chinese)
[5] Fan T Y and Byer R L 1988 *IEEE J. Quantum Electron.* **24** 895
[6] Sasaki T, Kojima T, Yokotani A, Oguri O and Nakai S 1991 *Opt. Lett.* **16** 1665
[7] Kintz G J and Baer T 1990 *IEEE J. Quantum Electron.* **26** 1457
[8] Tucker A W, Birnbaum M, Fincher C L and Erler J W 1977 *J. Appl. Phys.* **48** 4907
[9] Shen X H, Zhou F Z, Lin Z Q and Deng X M 1995 *Acta Opt. Sin.* **15** 797 (in Chinese)
[10] Siegman A E 1986 *Lasers* (Mill Valley: Californian University Science Books) 672
[11] Young M 1992 *Optics and Lasers* 4th edn (New York: Springer-Verlag) p 23
[12] Taira T, Mukai A, Nozawa Y and Kobayashi T 1991 *Opt. Lett.* **16** 1955
[13] Yariv A 1976 *Introduction to Optical Electronics* 2nd edn (New York: Holt, Rinehart and Winston) p 57
[14] Helmfrid S and Tatsuno K 1994 *J. Opt. Soc. Am.* B **11** 436
[15] Ding J H, Cui Y S and Wu M J 1987 *Laser's Theory and Application* (Beijing: Tsinghua University Press) p 132 (in Chinese)
[16] Lan X J, Yao J Q and An Y Y *et al* 1981 *Laser Technology* (Changsha: Hunan Science and Technology Press) 196 (in Chinese)
[17] Hansen P L, Pedersen C, Buchhave P and Skettrup T 1996 *Opt. Commun.* **127** 353
[18] Bierlein J D and Vanherzeele H 1989 *J. Opt. Soc. Am.* B **6** 622
[19] Shen N C, Zang E J, Cao H J, Zhao K, Lu H N, Zhang X B, Sun Y M, Xu C L, Chen X Z, Zhang K M and Bai X D 1999 *IEEE Trans. Instrum. Meas.* **48** 604