Appl. Phys. B 81, 633–636 (2005)
DOI: 10.1007/s00340-005-1944-9

Applied Physics B
Lasers and Optics

K. YANG✉
S. ZHAO
G. LI

Pulse symmetry and pulse duration compression in a diode-pumped doubly passively Q-switched $Nd:YVO_4$ lasers with Cr^{4+}:YAG and GaAs saturable absorbers

School of Information Science and Engineering, Shandong University, Jinan 250100, P.R. China

Received: 14 May 2005
Published online: 24 August 2005 •

ABSTRACT We present a simple technique to improve the symmetry of pulse emitted by doubly passively Q-switched lasers. Using both Cr^{4+}:YAG and GaAs saturable absorbers in the same cavity, a diode-pumped doubly passively Q-switched $Nd:YVO_4$ laser is realized for the fist time. This laser can generate more symmetric pulse with shorter pulse width and higher peak power compared with the solely passively Q-switched laser with Cr^{4+}:YAG saturable absorber or GaAs coupler. The pulse symmetry factor ε of such a doubly passively Q-switched laser is experimentally shown to reach 1.05. Simulations by a rate-equation model for doubly passively Q-switched laser are in close agreement with the experimental results.

PACS 42.55.Xi; 42.55.Rz; 42.60.Gd

1 Introduction

Diode-pumped solid-state passively Q-switched lasers that are capable of delivering optical pulses of nanosecond duration and thousands of HZ repetition rates in the near infrared region have a wide range of applications such as micro-surgeon, laser ranging, injection seeds for amplifiers, and remote sensing et al. [1–3]. In recent years, passive Q-switching of diode-pumped Nd-doped crystals, especially $Nd:YVO_4$ crystal, has been the most popular and concise method to get such laser sources, in which Cr^{4+}:YAG and GaAs have been used as passive Q-switches most widely and the pulses ranging from several to tens of nanoseconds have been obtained [4–9]. Although such solely passively Q-switched lasers can emit short pulses, most theoretical and experimental results show that the pulse temporal profiles are usually asymmetric, with a sharp rising edge and a slow falling edge in a Cr^{4+}:YAG passively Q-switched laser [4–6, 10], and with a slow rising edge and a sharp falling edge in a GaAs Q-switched laser [7–10]. In some applications, the symmetric pulse is more useful. For instance, when the symmetric pulse is used in high power lasers, there is no need to reshape it after amplification. If we use both Cr^{4+}:YAG and GaAs saturable absorbers simultaneously in the same cavity, it is possible to obtain more symmetric and shorter pulses with higher peak power according to their pulse characteristics.

In this paper, we report the experimental observation of the symmetric shorter pulses with higher peak power emitted in a diode-pumped doubly Q-switched $Nd:YVO_4$ laser with Cr^{4+}:YAG saturable absorber and GaAs coupler for the first time, to our knowledge. In this laser, GaAs has two roles; to generate short pulses, and to couple the pulses out of the cavity. Using the coupled rate equations considering the Gaussian transversal and longitudinal distributions of the intra-cavity photon density, we further simulated the characteristics of the emitted pulses in the above passively Q-switched $Nd:YVO_4$ lasers and the theoretical calculations agreed with the experimental results.

2 Experiment

2.1 *Experimental setup*

The experimental setup is shown schematically in Fig. 1. The pump source is a fiber-coupled laser-diode (made by Semiconductor Institute, Chinese Academic) which can provide a maximum cw output power of 5 W with a central wavelength of 808 nm at 22 °C. The output beam from the fiber bundle end, which is 800 μm in diameter, is focused in to the laser crystal with a spot size of about 440 μm and numerical aperture of 0.22 by a focusing optics (1.8 : 1 imaging module, Coherent Inc., USA). M_1 is a concave mirror with 150-mm curvature radius, AR (anti-reflectance) coated at 808 nm on the entrance end, HR (high-reflectance) coated at 1064 nm and HT (high-transmission) coated at 808 nm on the other face. The laser crystal is an a-axis-cut $Nd:YVO_4$ crystal with 1.0 at. % doping and dimension of $4 \times 4 \times 5\,mm^3$ and

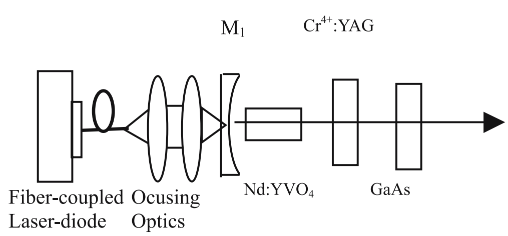

FIGURE 1 Experimental setup of the doubly Q-switched laser

✉ Fax: +86-531-88364613, E-mail: k.j.yang@sdu.edu.cn

is placed at the focused pump spot location. The crystal absorbed 85% of the incident pump power, corresponding to an effective absorption coefficient of $\alpha = 5.32\,\mathrm{cm}^{-1}$ at 808 nm. Its front surface is AR coated at 808 nm and its rear surface is AR coated at 1064 nm. To reduce the thermal loading in the laser crystal, the $Nd{:}YVO_4$ crystal is wrapped with indium foil and held in a copper block which is cooled at 20 °C by a semiconductor cooler. The small signal transmissions of the two Cr^{4+}:YAG saturable absorbers are $T_0 = 87\%$ and $T_0 = 91\%$, respectively. Both the surfaces of the Cr^{4+}:YAG saturable absorbers are AR coated at 1.06 μm. A 580-μm-thick uncoated GaAs wafer, which is optically polished on both sides, is used as both the saturable absorber and output coupler. The whole length of the cavity is 10 cm and the distance between Cr^{4+}:YAG and GaAs is 0.7 cm. A fast photoelectronic diode (response time is less than 1 ns) is used to receive the generated pulse. A PMD500AD laser power meter (Coherent-Molectron Inc., USA) is used to measure the average output power and a TED620B digital oscilloscope with bandwidths of 500 MHz (Tektronix Inc., USA) is used to measure the pulse width and the pulse repetition rate.

For comparison, we also measure the characteristics of the solely passively Q-switched $Nd{:}YVO_4$ laser with Cr^{4+}:YAG saturable absorber or GaAs coupler. When only the Cr^{4+}:YAG saturable absorber is used, a planar mirror with a transmission of 40% at 1.06 μm is employed as the output coupler. The transmission of 40% is similar to that of the uncoated GaAs wafer.

3 Experimental results

A summary of our experimental results is shown as scattered dots from Figs. 2 to 4. Figure 2 shows that the output powers of the double Q-switching are lower than the singly passive Q-switching with GaAs, however, slightly higher than that of Cr^{4+}:YAG. From Fig. 3, we can see that although the repetition rates of the double passive Q-switching are slightly reduced compared with single passive Q-switching with GaAs, the double passive Q-switching reduces the pulse duration and increases the pulse peak power in comparison with the sole passive Q-switching with Cr^{4+}:YAG saturable absorber or GaAs coupler. At the maximum incident pump power, the pulse durations are compressed by 64.7% and 29.3%, and the pulse peak powers are nearly improved by twice and one time, respectively. Figure 4 shows that the pulse duration and the repetition rates decrease with decreasing he small signal transmission of Cr^{4+}:YAG, while the pulse peak power increases at the same incident pump power for double passive Q-switching. The single pulse profiles of an oscilloscope trace of different Q-switching at the maximum pump power of 4.77 W and a small signal transmission $T_0 = 87\%$ of Cr^{4+}:YAG are shown as solid lines in Fig. 5. To compare the symmetry of different passive Q-switching, we define a symmetry factor ε as the ratio of the rising and the falling time of

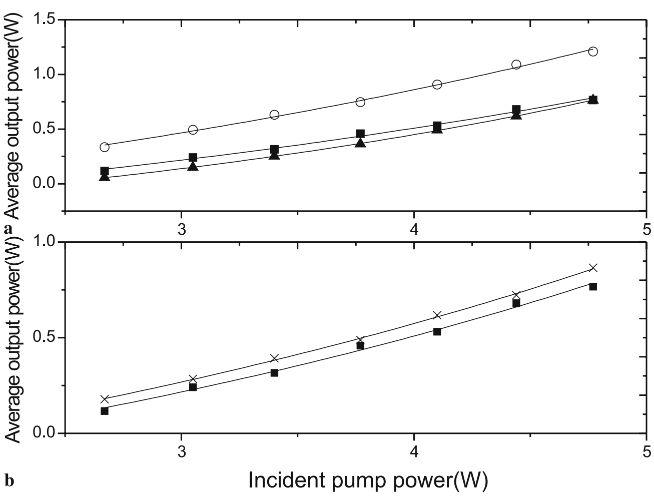

FIGURE 2 Average output power versus incident pump power: (**a**) three different passive Q-switching with the same Cr^{4+}:YAG of $T_0 = 87\%$; (**b**) double passive Q-switching with different small signal transmission of Cr^{4+}:YAG. The circles represent solely GaAs Q-switching, the squares double passive Q-switching with Cr^{4+}:YAG of $T_0 = 87\%$, the triangles solely Cr^{4+}:YAG Q-switching with $T_0 = 87\%$, the crosses double passive Q-switching with Cr^{4+}:YAG of $T_0 = 91\%$

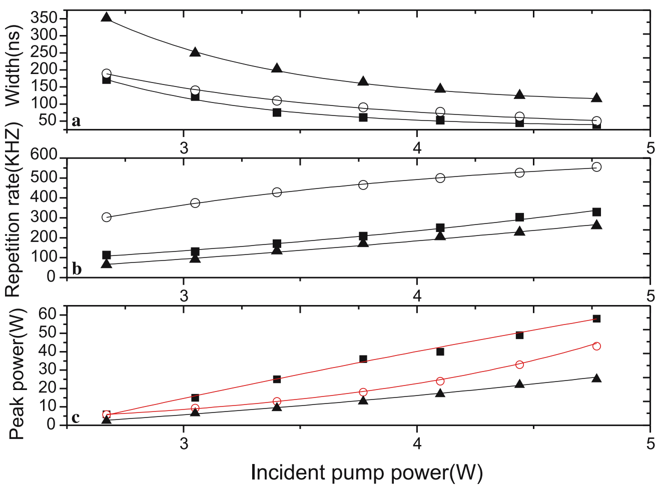

FIGURE 3 Dependence on pump power of pulse width, repetition rates and peak power by different Q-switching with the same Cr^{4+}:YAG of $T_0 = 87\%$: (**a**) pulse width; (**b**) repetition rates; (**c**) peak power. The symbols represent the same meanings as the ones in Fig. 2

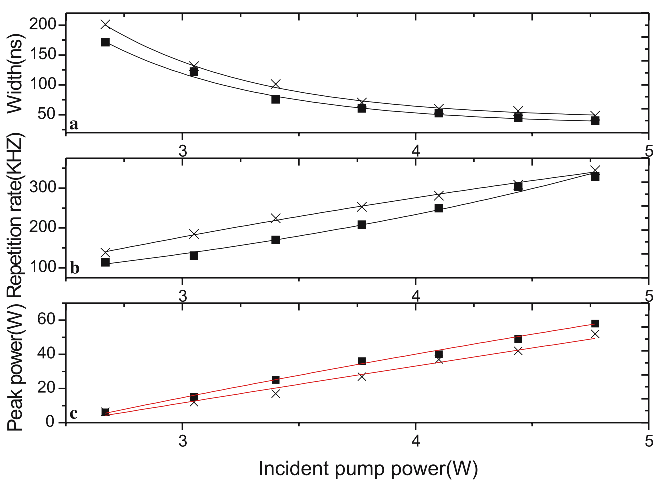

FIGURE 4 Dependence on pump power of pulse width, repetition rates and peak power by double passive Q-switching with different small signal transmissions of Cr^{4+}:YAG: (**a**) pulse width; (**b**) repetition rates; (**c**) peak power. The symbols represent the same meanings as the ones in Fig. 2

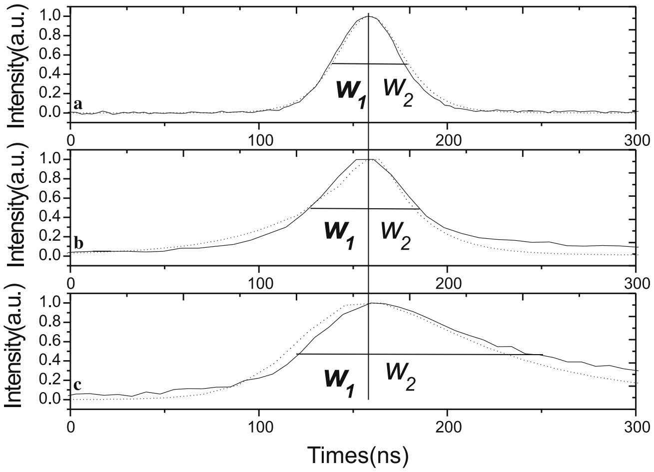

FIGURE 5 Typical pulse profiles from the Q-switched lasers: (**a**) double passive Q-switching; (**b**) GaAs Q-switching; (**c**) Cr^{4+}:YAG Q-switching

the pulse full width at half-maximum (FWHM), which can be expressed as:

$$\varepsilon = \frac{\omega_1}{\omega_2} \tag{1}$$

where ω_1 and ω_2 are the rising and falling times of pulse FWHM and shown in Fig. 5, respectively. In Fig. 5, (a) is the pulse profile of double passive Q-switching, which has a pulse duration of 41 ns with $\varepsilon = 1.05$; (b) is the pulse profile of solely passive Q-switching with GaAs, which has a pulse duration of 58 ns with $\varepsilon = 1.3$; (c) is the one of solely passive Q-switching with Cr^{4+}:YAG, which has a pulse duration of 116 ns with $\varepsilon = 0.48$. The analysis shows that double passive Q-switching not only can compress the pulse, but also increase the symmetry of the pulse.

4 Theoretical analysis

To better understand the phenomenon, we further use the coupled rate equations considering the Gaussian transversal and longitudinal distributions of the intra-cavity photon density to simulate the characteristics of the emitted pulses. For the doubly passively Q-switched laser, the extended coupled rate equations can be written as [8, 11]:

$$\int_0^\infty \frac{\mathrm{d}\varphi(r,t)}{\mathrm{d}t} 2\pi r \mathrm{d}r = \int_0^\infty \Bigg\{ \frac{1}{t_\mathrm{r}} \Bigg[2\sigma n(r,t) l \varphi_\mathrm{g}(r,t) - 2\sigma_\mathrm{g} n_{s1}(r,t) l_s \varphi_s(r,t) - 2\sigma_\mathrm{e} \left[n_{s0} - n_{s1}(r,t) \right] l_s \varphi_s(r,t) - 2\sigma^+ n^+(r,t) d \varphi_\mathrm{A}(r,t) - 2\sigma^0 \left[n_0 - n^+(r,t) \right] \mathrm{d}\varphi_\mathrm{A}(r,t) - B\varphi_\mathrm{A}^2(r,t) d - \ln\left(\frac{1}{R}\right) \varphi_\mathrm{A}(r,t) - L\varphi(r,t) \Bigg] \Bigg\} 2\pi r \mathrm{d}r \tag{2}$$

$$\frac{\mathrm{d}n(r,t)}{\mathrm{d}t} = R_\mathrm{in} \exp\left(-\frac{2r^2}{\varpi_\mathrm{p}^2}\right) - \sigma c n(r,t) \varphi_\mathrm{g}(r,t) - \frac{n(r,t)}{\tau} \tag{3}$$

$$\frac{\mathrm{d}n_{s1}(r,t)}{\mathrm{d}t} = \frac{(n_{s0} - n_{s1}(r,t))}{\tau_s} - \sigma_\mathrm{g} n_{s1}(r,t) c \varphi_s(r,t) \tag{4}$$

$$\frac{\mathrm{d}n^+(r,t)}{\mathrm{d}t} = \left[\sigma^0 \left(n_0 - n^+(r,t) \right) - \sigma^+ n^+(r,t) \right] c \varphi_\mathrm{A}(r,t) \tag{5}$$

where $n(r,t)$ is the average population-inversion density in Nd:YVO_4; n_{s0} and $n_{s1}(r,t)$ are the population densities of the ground-state and the excited-state in Cr^{4+}:YAG; n_0 is the total population density of the EL2 defect level (including $EL2^0$ and $EL2^+$) of GaAs; $n^+(r,t)$ is the population density of positively charged $EL2^+$ in GaAs, and σ^0 and σ^+ are the absorption cross sections of $EL2^0$ and $EL2^+$ in GaAs; c is the velocity of light in vacuum; $R_\mathrm{in} = P_\mathrm{in}[1 - \exp(-\alpha l)]/(h\upsilon_p \pi \varpi_p^2 l)$ is the volume pumping rate, where P_in is the incident pump power, α is the absorption coefficient of the Nd:YVO_4 crystal, $h\upsilon_p$ is the photon energy of the pump beam, ϖ_p is the average radius of the pump light in the gain medium; $t_\mathrm{r} = 2L_c/c$ is the round-trip time in resonator with optical length of the cavity $L_c = n_1 l + n_2 l_s + n_3 d + (L_p - l - l_s - d)$, in which n_1, n_2, and n_3 are the refractive indices of Nd:YVO_4 gain medium, Cr^{4+}:YAG saturable absorber, and GaAs wafer, respectively, L_p is the physical cavity length, l is the length of Nd:YVO_4, l_s is the thickness of Cr^{4+}:YAG, which is determined by the small signal transmission $T_0 = \exp(-\sigma_\mathrm{g} n_{s0} l_s)$, d is the thickness of the GaAs wafer; σ_g and σ_e are the ground-state and the excited-state absorption cross sections of Cr^{4+}:YAG; L is the intrinsic loss including the inserting loss of Cr^{4+}:YAG; σ and τ are the stimulated-emission cross section and the stimulated-radiation lifetime of Nd:YVO_4 crystal, respectively; τ_s is the excited-state lifetime of Cr^{4+}:YAG; $B = 6\beta h\nu c(\omega_\mathrm{g}/\omega_\mathrm{A})^2$is the coupling coefficient of TPA in GaAs, where β is the absorption coefficient of two photons, $h\nu$ is the photon energy of the fundamental wave, ω_g and ω_A are the radii of the TEM_{00} mode at the positions of the Nd:YVO_4 crystal and GaAs wafer, respectively, R is the Fresnel reflectivity of the Fabry–Perot (FP) cavity formed by GaAs, which is defined as [12]:

$$R = \frac{R_0 \left(1 - \exp\left(-\alpha_\mathrm{a} d\right)\right)^2 + 4R_0 \exp\left(-\alpha_\mathrm{a} d\right) \sin^2(\delta/2)}{\left(1 - R_0 \exp\left(-\alpha_\mathrm{a} d\right)\right)^2 + 4R_0 \exp\left(-\alpha_\mathrm{a} d\right) \sin^2(\delta/2)} \tag{6}$$

where $\delta/2 = (2\pi/\lambda)nd$, n is the refractive index of GaAs at 1.06 μm, $R_0 = 0.3$ is the reflection coefficient at both facets of the GaAs and α_a is the absorption coefficient of GaAs at 1.06 μm, which is reported to be 1.1 cm^{-1} [12]. According to the parameters, $R = 63\%$ can be obtained.

$\varphi(r,t)$ is the photon density; $\varphi_\mathrm{g}(r,t)$, $\varphi_\mathrm{s}(r,t)$ and $\varphi_\mathrm{A}(r,t)$ are the photon densities at the positions of Nd:YVO_4 crystal, Cr^{4+}:YAG saturable absorber, and GaAs wafer, respectively, which are expressed as [11]:

$$\varphi_n(r,t) = \frac{\omega_l^2}{\omega_n^2} \varphi(0,t) \exp\left(-\frac{2r^2}{\omega_n^2}\right) \qquad (n = g, s, A) \tag{7}$$

where ω_g, ω_s and ω_A are the radii of the TEM_{00} mode at the positions of the Nd:YVO_4 crystal, Cr^{4+}:YAG saturable absorber and GaAs wafer, respectively, ω_l is the average radius of the oscillating TEM_{00} mode in the laser cavity. Using the well-known ABCD theory, we can obtain the radius of

Parameters	Values	Parameters	Values
σ	2.5×10^{-18} cm^2	l	0.5 cm
σ_g	4.3×10^{-18} cm^2	l_s	0.11cm
σ_e	8.2×10^{-18} cm^2	d	580 µm
n_{s0}	2.0×10^{17} cm^{-3}	L	0.02
σ^0	1.0×10^{-16} cm^2	α	5.32 cm^{-1}
σ^+	2.3×10^{-17} cm^2	ω_p	220 µm
τ	98 µs	ω_g	180 µm
τ_s	3.2 µs	ω_A	150 µm
n_1	2.19	n_0	1.2×10^{16} cm^{-3}
n_2	1.81	n^+	1.4×10^{15} cm^{-3}
n_3	3.299	L_p	10 cm
β	2.6×10^{-8} cm W^{-1}		

TABLE 1 The parameters of the theoretical calculation [6, 9, 11]

the TEM_{00} mode at any position of the cavity, including ω_g, ω_s and ω_A. In this letter, the cavity employed is a plannar-concave cavity, so the beam waist is on the output coupler. We define ω_l as the average value of the beam radii on the output coupler and the concave mirror M_1.

Based on the coupled rate equations describing the doubly passively Q-switched Nd:YVO_4 lasers with Cr^{4+}:YAG saturable absorber and GaAs wafer, we can also get the rate equations of the solely passively Q-switched Nd:YVO_4 lasers with Cr^{4+}:YAG saturable absorber or GaAs wafer, by removing the terms describing GaAs wafer or Cr^{4+}:YAG saturable absorber, respectively. Using the parameters shown in Table 1 and the methods in [12], we can numerically solve the rate equations from (2) to (5) on a computer. The calculated average output powers are shown as solid lines in Fig. 2. The dependences of the pulse width, repetition rates and peak power on pump power are shown by solid lines in Figs. 3 and 4. The dotted lines in Fig. 5 are the simulated pulse profile of the abovementioned different passively Q-switched lasers. In Fig. 5, (a) is the simulated pulse profile of double passive Q-switching, which has a pulse duration of 40 ns with $\varepsilon = 1.02$; (b) is the pulse profile of solely passive Q-switching with GaAs, which has a pulse duration of 60 ns with $\varepsilon = 1.4$; (c) is the one of solely passive Q-switching with Cr^{4+}:YAG, which has a pulse duration of 110 ns with $\varepsilon = 0.57$. From Figs. 3 to 5, we can see that the theoretical results are in agreement with the experimental results. Both the theoretical analysis and the experimental results show that double passive Q-switching not only can increase the symmetry of the pulse, but also compress the pulse duration and increase the pulse peak power.

5 Conclusions

In conclusion, we have experimentally observed much more symmetric pulses with higher peak power and the compression of the pulse duration in a doubly passively Q-switched Nd:YVO_4 laser with both Cr^{4+}:YAG saturable absorber and GaAs coupler used simultaneously. Using the extended rate equation model considering the Gaussian transversal and longitudinal distributions of the intra-cavity photon density, we also numerically studied the characteristics of such a laser. The numerical results agree well with the experimental results. Both results shows that the doubly passively Q-switched Nd:YVO_4 laser can emit much more symmetric pulse with shorter pulse width and higher peak power.

ACKNOWLEDGEMENTS This work is partially supported by the National Science foundation and the Science and Technology Development Program of Shangdong Province.

REFERENCES

1 G.J. Friel, R.S. Conney, A.J. Kemp, B.D. Sinclair, J.M. Ley: Appl. Phys. B **67**, 267 (1998)
2 Y.F. Chen, Y.P. Lan: Appl. Phys. B **74**, 415 (2002)
3 C. Li, J. Song, D. Shen, N. Kim, J. Lu, K. Ueda: Appl. Phys. B **70**, 471 (2000)
4 H. Chen, E. WU, H. Zeng: Opt. Commun. **230**, 175 (2003)
5 Y.F. Chen, Y.C. Chen, S.W. Chen, Y.P. Lan: Opt. Commun. **234**, 337 (2004)
6 G.Q. Li, S.Z. Zhao, K.J. Yang, H.M. Zhao: Opt. Eng. **43**, 2762 (2004)
7 P. Li, Q. Wang, X. Zhang, Y. Wang, S. Li, J. He, X. Lu: Opt. Laser Technol. **33**, 383 (2001)
8 Z. Li, Z. Xiong, N. Moore, G.C. Lim, W.L. Huang, D.X. Huang: Opt. Commun. **237**, 411 (2004)
9 G.Q. Li, S.Z. Zhao, K.J. Yang, D.C. Li, J. Zou: Opt. Exp. **13**, 1178 (2005)
10 T. Erneux, P. Peterson, A. Gavrielides: Eur. Phys. J. D. **10**, 423 (2000)
11 K. Yang, S. Zhao, G. Li, H. Zhao: Jpn. J. Appl. Phys. **43**, 8053 (2004)
12 G.Q. Gu, F. Zhou, G. Zhang, M.K. Chin: Electron Lett. **34**, 564 (1998)