Suppressing the preferential σ-polarization oscillation in a high power $Nd:YVO_4$ laser with wedge laser crystal*

Zheng Yao-Hui(郑耀辉)†, Zhou Hai-Jun(周海军), Wang Ya-Jun(王雅君), and Wu Zhi-Qiang(邬志强)

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006*, China*

(Received 23 November 2012; revised manuscript received 27 February 2013)

We observe the phenomenon of priority oscillation of the unexpected σ-polarization in high-power $Nd:YVO_4$ ring laser. The severe thermal lens of the σ-polarized lasing, compared with the π-polarized lasing, is the only reason for the phenomenon. By designing a wedge $Nd:YVO_4$ crystal as the gain medium, the unexpected σ-polarization is completely suppressed in the entire range of pump powers, and the polarization stability of the expected π-polarized output is enhanced. With the output power increasing from threshold to the maximum power, no σ-polarization lasing is observed. As a result, 25.3 W of stable single-frequency laser output at 532 nm is experimentally demonstrated.

Keywords: high-power laser, single-frequency, thermal effect, polarization selection

PACS: 42.55.Xi, 42.60.Da, 42.60.Lh, 42.60.Pk **DOI:** 10.1088/1674-1056/22/8/084207

1. Introduction

The development of all-solid-state high-power single-frequency laser sources is necessary for many applications, such as laser telemetry, laser spectroscopy, optical holography, nonlinear optics,[1,2] and quantum information. Neodymium-doped yttrium vanadate ($Nd:YVO_4$) is a suitable laser crystal for a diode pumped laser owing to its high emission and high absorption cross section.[3–5] The $Nd:YVO_4$ crystal is naturally birefringent, the stimulated emission cross sections (SECS) are not equal in different crystallographic directions. The π-polarized lasing (lasing parallel to the c axis) is stronger in the $Nd:YVO_4$ crystal, compared with the σ-polarized lasing (lasing perpendicular to the c axis).[6] Lasers built with this crystal will therefore preferentially oscillate on the π-polarization and keep the polarization direction unchanged in the entire range of pump powers, in the absence of other effects that create a bias for the σ-polarization.[7,8] The stability of polarization direction is necessary for obtaining the robust unidirectional operation and the nonlinear phase-matching in intracavity frequency-doubling ring lasers.

However, the difference of SECS between the orthogonal directions is not enough to make lasing keep on π-polarization in all cases. For this reason, the laser crystal is cut in a wedge for special aims. In 2010, our group reported a single-frequency $Nd:YVO_4$ laser with good power stability by using a wedge crystal as the polarized beam splitter, which eliminated the possible change of polarized direction caused by the nonlinear loss.[8] In addition, in order to enhance the passive Q-switching effect of Q-switched lasers,[9] Agnesi *et al.* designed a wedge $Nd:YVO_4$ crystal that confined the polarization direction on the σ-polarization with a low SECS.[10] A wedge Nd:YLF crystal was also used as a polarization selector to confine the polarization direction of the output beam.[11]

We recently demonstrated an efficient generation of 25.3-W single-frequency output at 532 nm by intracavity frequency doubling in a diode-pumped $Nd:YVO_4$ ring laser, using lithium triborate (LBO) as the doubling medium. Limited by the stable region of the high-power laser cavity, some special phenomena that differed from the low-power lasers appeared.

We noticed that the σ-polarization oscillated prior to π-polarization, with a usual (unwedge) crystal as the gain medium, due to the orthogonally-polarized different thermal lens. This is the first time that the preferential σ-polarization oscillation is observed in the absence of other effects, such as those mentioned in Refs. [9]–[11]. By measuring the thermal lens of π-polarization and σ-polarization, and analyzing the stable range of the laser cavity, we found the reason for this phenomenon.

Subsequently, by employing a wedge $Nd:YVO_4$ crystal as the gain medium, we constrained the laser to oscillate on π-polarization mode without σ-polarization oscillation in the entire range of pump powers.

2. Basic mechanism and experimental setup

In a $Nd:YVO_4$ crystal, the birefringent wavelength difference is negligible (both π and σ-polarization wavelengths peak at 1064 nm) with the π-polarized emission exhibiting a larger cross section than the σ-polarized one. In normal circumstances, the stronger π-polarized emission makes the

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2011AA030203), the National Basic Research Program of China (Grant No. 2010CB923101), the National Natural Science Foundation of China (Grant No. 61008001), and the Natural Science Foundation of Shanxi Province, China (Grant No. 2011021003-2).

†Corresponding author. E-mail: yhzheng@sxu.edu.cn

laser output at 1064 nm show linear polarization along the π-polarized direction due to the gain competition. However, in the case of high-power lasers, because the thermal focal length is a variable related to the pump power, it is difficult to design a resonator which satisfies the stable condition in the whole power range. The resonator is usually optimized to the best in the local region of the maximum power point,[12] and cannot reach the stable region in the low pump power. Since the thermal effect of σ-polarization is stronger than that of π-polarization, the σ-polarization prior to the π-polarization, reaches the stable region during the process of increasing the pump power. As a result, the unexpected σ-polarization oscillates preferentially. With the increase of the pump power, the laser mode is transformed into π-polarization subsequently due to the gain competition.

To examine this prediction of the preferential σ-polarization oscillation and its suppression scheme, we built a high-power single-frequency intracavity frequency-doubling Nd:YVO_4 laser as shown in Fig. 1 (the dashed diagram shows that the gain medium is instead by an unwedged Nd:YVO_4 crystal with the same configuration). The pump source was a fiber-coupled diode laser, whose output was a partial polarized beam, with the central wavelength of 888 nm to mitigate the thermal effect.[13,14] An asymmetric bow-tie ring resonator was implemented to accommodate the laser diode single-end longitudinal pumping scheme,[15] with an α-cut laser crystal positioned between the convex mirrors M_1 and M_2 ($R = -1500$ mm). Two pieces of composite Nd:YVO_4 crystals of 23-mm-length (including undoped end cap of 3 mm, Nd-doped part of 20 mm) with Nd concentration of 0.8% were used, respectively, one was usual shaped with two end facets parallel, the other was specially designed with a wedge end-facet of two degree. The nonlinear crystal LBO, which was controlled at the non-critical phase-matching temperature of 149 centigrade, was placed between the concave mirrors M_3 and M_4 ($R = 100$ mm), thus a smaller waist was formed to obtain high nonlinear conversion efficiency. Unidirectional operation was achieved with an optical diode consisting of a TGG (terbium gallium garnet) Faraday rotator rod and half-wave plate providing the necessary polarization rotation compensation. The etalon was used as a spectral filter to narrow the gain bandwidth and ensured the stable of the single-frequency operation.[18,19]

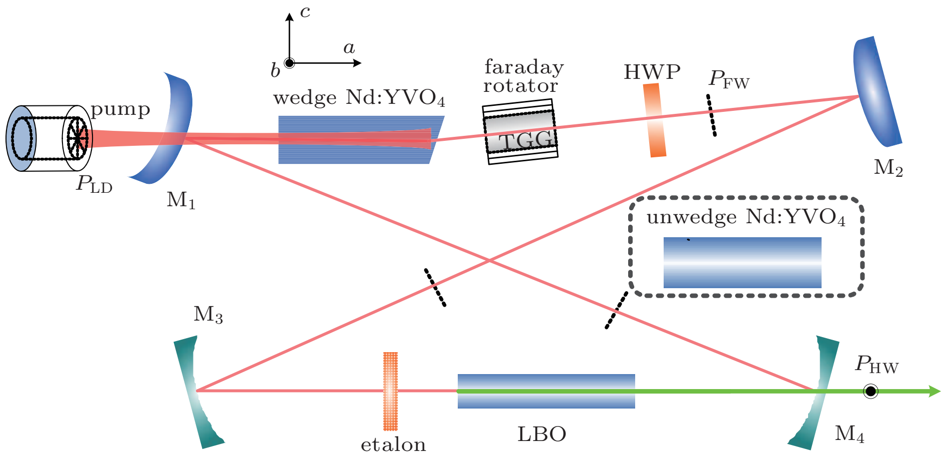

Fig. 1. (color online) Experimental setup of the single-frequency green laser. Nd:YVO_4-Neodymium-doped yttrium vanadate, TGG-terbium gallium garnet, HWP-half wave plate, LBO-lithium triborate, P_{LD}, P_{FW}, and P_{HW} are the polarized directions of the laser diode, the fundamental wave and the harmonic wave, respectively.

For an α-cut Nd:YVO_4 crystal, due to the different thermal optical coefficients dn/dT in the two crystallographic directions ($dn_o/dT = 8.5 \times 10^{-6}$/K, σ-polarized lasing; $dn_e/dT = 2.9 \times 10^{-6}$/K, π-polarized lasing), each polarization in two crystal directions experiences different thermal lens.[20] Therefore, we evaluate that the thermal effect of σ-polarization should be severer than that of π-polarization.[21,22] In order to confirm the inference, a probe beam was used to measure the values of the thermal focus of π-polarized and σ-polarized beams.[23] The measured results are shown in Fig. 2. For the same absorption pump power, the thermal focal length of σ-polarized beam is shorter than that of the π-polarized beam. According to the measured values, we can establish the relation between the absorption pump power and the thermal focal length for each polarization beam.

On the basis of the measured results of the thermal focal length of the π-polarized beam, we designed a laser resonator using ABCD transfer matrix. In this calculation, the condition of the laser stable mode operation, $|A+D| < 2$, was applied. In order to make the laser operate stable under the condition of high powers, the distance between M_3 and M_4 was set to 101 mm (the remainder part of the four-mirror ring cavity was 383 mm). However, inevitably, the design could not meet the requirement for low power operation. The function of the mode radius in the laser crystal ω versus thermal focal length f_t is shown in Fig. 3. It can be seen that only when the thermal focal length f_t is in the range between 65 mm and 243 mm, the laser can operate in the stable region. The higher the pump power is, the shorter the f_t is. When the pump power is lower, the f_t is longer than 243 mm and therefore, the laser cannot meet the condition of stable oscillation.

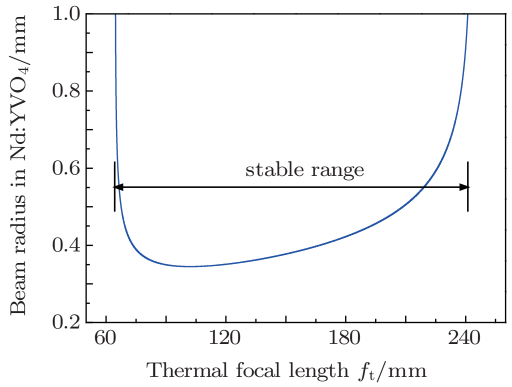

Fig. 2. (color online) Beam radius of fundamental wave in Nd:YVO$_4$ as a function of thermal focal length of the Nd:YVO$_4$ crystal.

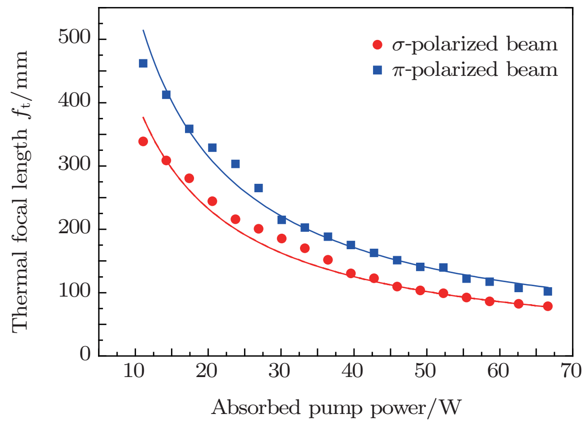

Fig. 3. (color online) The measured thermal focal lengths for π-polarized and σ-polarized lasing at different pump powers, which show that the thermal effect of σ-polarized lasing is severer than that of π-polarized lasing.

Owing to the difference of thermal effect, the relationship between ω and f_t cannot describe intuitively the stable condition of two orthogonal polarizations of the laser. The combination of Fig. 2 and the fitting results of Fig. 3 allows us to build the function between ω of π-polarized (σ-polarized) and the absorption pump power. Figure 4 is the analysis results, the real and dot lines represent the π-polarized lasing and σ-polarized lasing, respectively. One can see that the two polarization beams present a significant discrepancy of the beam size and the stable region. This is caused by the difference of the $\mathrm{d}n/\mathrm{d}T$ between π-polarized lasing and σ-polarized lasing and the resonator design. The σ-polarized beam reaches the stable region prior to the π-polarized beam. With the increase of pump power, the π-polarized lasing reaches the stable region gradually. The π-polarized lasing and σ-polarized lasing compete mutually until the π-polarized lasing oscillates stably. Thus, during the process of increasing the pump power, the laser may go through three stages: σ-polarized lasing, π-polarized and σ-polarized competition, π-polarized lasing. The phenomenon affects the laser operated on stable linear polarization and kept phase-matching of intracavity frequency doubling.

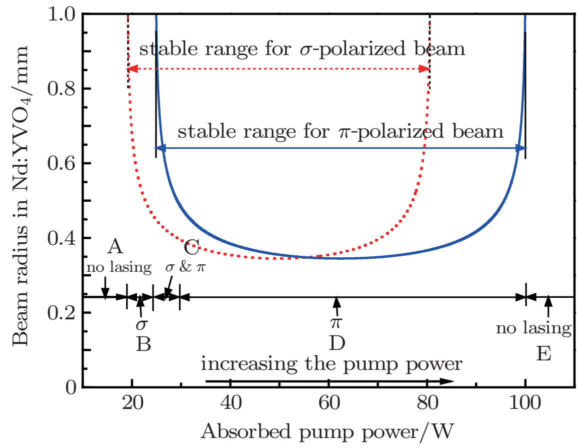

Fig. 4. (color online) Comparison of the stable regions of π-polarized lasing and σ-polarized lasing. A–E are the regions of different polarized beams operation of our laser system obtained from experimental results. Regions A and E are without lasing operation. B is the σ-polarized beam operation region. Region C is the competition of σ-polarized lasing and π-polarized lasing. Region D is the π-polarized operation.

In order to avoid this problem, we need to create a bias for the σ-polarized lasing. An alternative is to use a wedged Nd:YVO$_4$ crystal based on its natural birefringence. As a result, the wedge causes spatial walk-off between the π-polarized lasing and σ-polarized lasing at the exit of the wedge facet. The spatial walk-off angle ρ of beam propagating at a wedge angle α with respect to the c axis is given by

$$\rho = \arcsin(n_e \sin\alpha) - \arcsin(n_o \sin\alpha).$$

The walk-off angle ρ increases monotonously with the increase of α. However, limited by the total reflection angle of the wedge facet, a maximum of 11.5-deg walk-off can be obtained at a wedge angle α of 25.6 deg. The large walk-off angle is enough to make the wedge Nd:YVO$_4$ act as a polarizing beam splitter. Therefore, the two polarizations cannot keep aligning in the resonator at the same time. When the laser is forced to be operated on π-polarization by aligning them, the σ-polarization must separate from the aligning axis formed by the π-polarization beam, and be thoroughly suppressed by introducing the cavity loss to the polarization mode. The design will make the π-polarization stable in the entire range of pump powers which is available to us.

3. Experimental results and analysis

The following experiments were carried out to demonstrate the phenomena in the high-power laser. Both Nd:YVO$_4$

crystals, including unwedge and wedge ones with the same size and doping concentration, were employed as the gain medium, respectively. We carried out simultaneous observations of the output power and polarization direction of the laser while varying the absorption pump power from the threshold to 80 W.

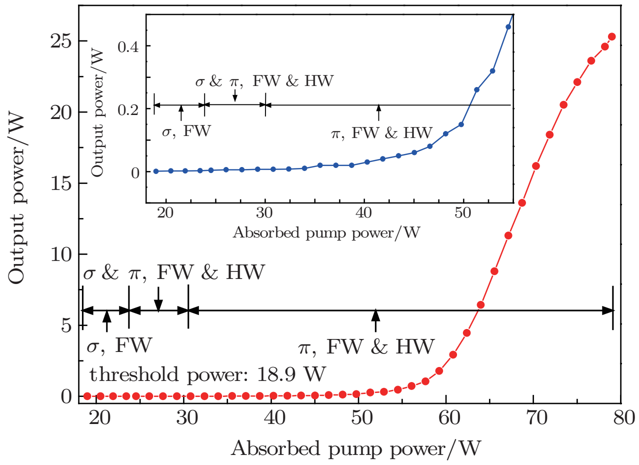

Fig. 5. (color online) Laser output power versus absorption pump power in the case of unwedge Nd:YVO_4 crystal with the competition of σ-polarized lasing. σ, FW: σ-polarized fundamental wave; σ & π, FW & HW: σ-polarized and π-polarized fundamental wave and the generation of harmonic wave of π-polarized lasing; π, FW & HW: π-polarized fundamental wave and its harmonic wave. The inset is the magnifying y axis in the range of threshold to 55 W of the absorbed pump power.

First, in the case of unwedged Nd:YVO_4 crystal, we measured the output characteristic of the laser, as shown in Fig. 5. The threshold power is about 18.9 W. When the laser is operated near the threshold, it has only fundamental wave output along the σ-polarization direction, which was checked by a polarizer. The harmonic wave output is not observed for the time being. The phenomenon is different from that of the low power laser. The working state corresponds to the region B of Fig. 4, where only the σ-polarization is in the stable region. In addition, since the σ-polarization fundamental wave does not satisfy the phase-matching condition of the LBO crystal, there is no harmonic wave output in this region. As the pump power increases, the harmonic wave arises accompanied by π-polarization (region C). However, the harmonic wave cannot keep stable operation, and only flickers at random. It is caused by the fact that the laser is in the region C of Fig. 4 and the two polarizations compete mutually. There are two reasons related to the polarization competition: one is the fact that π-polarization lasing is located at the edge of the stable region, and its diffraction loss is higher, therefore, the net gains of two polarization directions are approximately equal. Another reason is the intracavity frequency-doubling process, π-polarization lasing satisfies the condition of nonlinear conversion, however, σ-polarization lasing does not. When the pump power is increased further, the lasing switches completely to π-polarization, and the harmonic wave can keep stable operation until the pump power reaches the maximum value due to the larger SECS of the π-polarization lasing. The process corresponds to the region D of Fig. 4. During the whole process of pump power increasing, the working state of the laser could be divided into three stages: σ-polarized lasing (B), π-polarized lasing and σ-polarized lasing competition (C), π-polarized lasing (D). The experimental results reveal that although the π-polarization lasing has a larger SECS compared with the σ-polarization lasing, it cannot oscillate prior to σ-polarization in high power lasers. The phenomenon is completely in conformity with the former analysis.

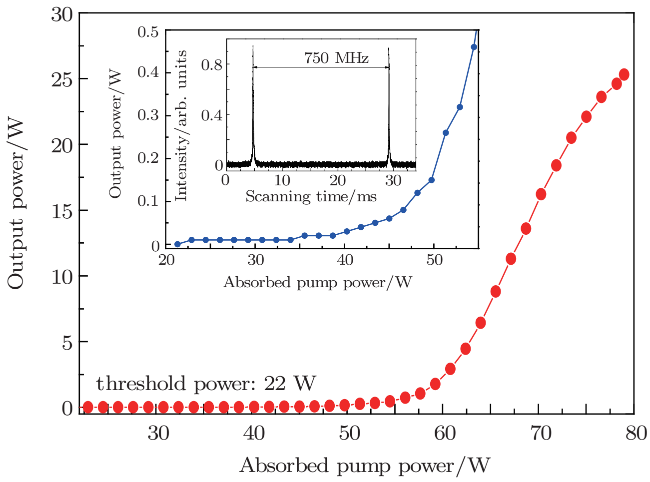

Fig. 6. (color online) Laser output power versus absorption pump power in the case of wedge Nd:YVO_4 crystal with stable π-polarized beam oscillation and its harmonic wave without the competition of σ-polarized lasing. The bigger inset shows the magnified y axis in the range of the threshold to 55 W of the absorbed pump power, and the smaller one is the transmission signal of the scanning confocal Fabry–Pérot cavity.

In order to eliminate the influence of the preferential σ-polarization oscillation, we carried out the above experiment process by using a wedge Nd:YVO_4 crystal as the gain medium. The wedge angle α was two-degree, which could create a walk-off angle ρ of 0.5 degree, which was enough to separate spatially the two polarization beams, and suppressed the unexpected σ-polarized fundamental wave. The experimental results are shown in Fig. 6, the inset of which indicates that the laser is in single-longitudinal-mode operation. In the case, the threshold of the laser is 20 W or so, which is obviously higher than that of the unwedged Nd:YVO_4 laser, which is due to the suppressed σ-polarization. When the laser operated from threshold to the maximum pump power, the fundamental wave output still operates on the π-polarization and the harmonic wave output increases monotonously with the increase of pump power. For the entire range of pump powers, no polarization competition or harmonic flicker is observed. The maximum output power of the laser is 25.4 W, including the harmonic wave (25.27 W) and the fundamental wave (130 mW).

4. Conclusion

In summary, we observed a phenomenon of priority oscillation of the unexpected σ-polarization in a high-power laser when an unwedged Nd:YVO_4 crystal was used as the gain medium. The basic mechanism involves that σ-polarized lasing has a more severe thermal lens than the π-polarized lasing due to different thermal optical coefficients $\mathrm{d}n/\mathrm{d}T$ in the two crystallographic directions. The severe thermal lens can make the σ-polarization reach the stable range of the cavity prior to π-polarization during the process of increasing pump power. With the increase of pump power, the σ-polarization reaches the stable region and begins to oscillate. In the entire range of pump powers, the laser goes through three stages: σ-polarized lasing, σ-polarized and π-polarized competition, and π-polarized lasing. Therefore, for the entire range of pump powers, the fundamental wave undergoes different polarization directions, which is disadvantageous to the stable operation and the intracavity frequency doubling. In order to eliminate the influence of the preferential σ-polarization, we designed a wedge Nd:YVO_4 crystal as the gain medium, suppressing the unexpected σ-polarization oscillation, enhancing the polarization stability. Finally, we obtained a 25.3-W single-frequency green laser output. In the whole range of pump powers, no polarization competition or harmonic flicker was observed.

References

[1] Liu J L, Liu Q, Li H, Li P and Zhang K S 2011 *Chin. Phys. B* **20** 114215

[2] Ding X, Zhang S M, Ma H M, Pang M, Yao J Q and Li Z 2008 *Chin. Phys. B* **17** 211

[3] X Delen, F Balembois and P Georges 2011 *J. Opt. Soc. Am. B* **28** 972

[4] Peng X Y, Xu L and Asundi A 2002 *IEEE J. Quantum Electron.* **38** 1291

[5] Ning J P and Shang L J 2005 *Chin. Phys.* **14** 1387

[6] Suzuki K, Shimomura K, Eda A and Muro K 1994 *Opt. Lett.* **19** 1624

[7] Zhu P, Li D J, Hu P X, Schell A, Shi P, Haas C R, Wu N L and Du K M 2008 *Opt. Lett.* **33** 1930

[8] Zheng Y H, Li F Q, Wang Y J, Zhang K S and Peng K C 2010 *Opt. Commun.* **283** 309

[9] Chen Y F and Lan Y P 2002 *Appl. Phys. B* **74** 415

[10] Agnesi A and Acqua S D 2003 *Appl. Phys. B* **76** 351

[11] Huang Y J, Tang C Y, Lee W L, Huang Y P, Huang S C and Chen Y F 2012 *Appl. Phys. B* **108** 313

[12] Wang Y J, Zheng Y H, Xie C D and Peng K C 2011 *IEEE J. Quantum Electron.* **47** 1006

[13] McDonagh L, Wallenstein R, Knappe R and Nebel A 2006 *Opt. Lett.* **31** 3297

[14] McDonagh L and Wallenstein R 2007 *Opt. Lett.* **32** 802

[15] Martin K I, Clarkson W A and Hanna D C 1996 *Opt. Lett.* **21** 875

[16] Liu H and Gong M L 2012 *Chin. Phys. B* **21** 104208

[17] Wang Y Y, Xu D G, Liu C M, Wang W P and Yao J Q 2012 *Chin. Phys. B* **21** 094212

[18] Zheng Y H, Lu H D, Li F Q, Zhang K S and Peng K C 2007 *Appl. Opt.* **46** 5336

[19] Camargo F A, Willette T Z, Badr T, Wetter N U and Zondy J J 2010 *IEEE J. Quantum Electron.* **46** 804

[20] Bermudez J C, Pinto-Robledo V J, Kiryanov A V and Damzen M 2002 *Opt. Commun.* **210** 75

[21] Innocenzi M E, Yura H T, Fincher C L and R A Fields 1990 *Appl. Phys. Lett.* **56** 1831

[22] Jacinto C, Catunda T, Jaque D, Bausa L E and Garcia 2008 *Opt. Express* **16** 6317

[23] Hardman P J, Clarkson W A, Friel G J, Pollnau M and Hanna D C 1999 *IEEE J. Quantum Electron.* **35** 647