Polarization switching in a quasi-isotropic microchip Nd:YAG laser induced by optical feedback*

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(Received 30 May 2009; revised manuscript received 25 June 2009)

This paper demonstrates the influence of external optical feedback on the polarization state of longitudinal modes in quasi-isotropic microchip Nd:YAG lasers. Under optical feedback, the polarization state of longitudinal modes in quasi-isotropic lasers relies strongly on the intracavity anisotropy loss and mode competition. When the intracavity anisotropy loss is small, external optical feedback can cause polarization switching and strong mode competition between two orthogonal linearly polarized eigenstates of one laser longitudinal mode, which leads to the distortion of laser intensity modulation waveform. The polarization switching is independent of the initial external cavity length. By increasing the intracavity anisotropy loss, one polarization eigenstate can be suppressed and the laser works in single-polarization state. A theoretical analysis based on the compound cavity model is presented, which is in good agreement with the experimental results. The results offer guidance to the development of laser feedback interferometers.

Keywords: microchip Nd:YAG laser, optical feedback, polarization switching, laser feedback interferometer

PACC: 4225J, 4255R

1. Introduction

By reflecting a portion of the laser output back into the laser resonator from a movable external reflector or object, we find that the interference between the reinjected field and the stationary field causes laser intensity modulation, from which the displacement or velocity of the external object can be recovered. The signal characteristics of the modulated laser output intensity are similar to those with two-beam interference. One period of laser intensity undulation (one fringe) corresponds to a $\lambda/2$ change of the external cavity length, where λ represents the laser wavelength; that is why the phenomenon of optical feedback, first reported by King and Steward,[1] is also called a self-mixing interference. Due to its inherent simplicity, compactness, robustness, and economy, the laser feedback technique has been widely used for measurements of Doppler velocity,[2,3] displacement,[4,5] distance,[6,7] profile,[8,9] and vibration.[10,11] In recent years, diode-pumped microchip lasers[12,13] have attracted much attention for their ultrahigh sensitivity to optical feedback. However, the influence of optical feedback on the polarization states in quasi-isotropic microchip Nd:YAG lasers still lacks study. This study is essential to the self-mixing sensing research of microchip lasers, especially self-mixing interferometers, for it has great influence upon the intensity modulation.

This paper reports the influence of external optical feedback on the polarization state of longitudinal modes in quasi-isotropic microchip lasers. There exist two orthogonal linearly polarized eigenstates for each longitudinal mode order in quasi-isotropic lasers, while usually only single polarization is output due to large intracavity anisotropic loss and strong mode competition. When external optical feedback is introduced, one can observe the phenomena that intensities of two orthogonal linearly polarized eigenstates both are modulated by the external cavity length, the periodical polarization switching and intensity transfer between two eigenstates. The polarization switching is independent of the initial external cavity length. The feedback-induced intensity modulation waveforms are affected by the polarization switching. By inserting a tilted waveplate into the laser resonator to increase the intracavity anisotropy loss in the laser, normal intensity modulation waveforms can be recovered. The results offer guidance to the development of laser feedback interferometers.

*Project supported by the National Natural Science Foundation of China (Grant No. 30870662).

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2. Experimental setup

Experiments are carried out on a diode pumped open-cavity Nd:YAG laser operating at 1.06 μm with single longitudinal mode. The experimental setup resembles the structure of a laser feedback interferometer, as shown schematically in Fig. 1. The laser chip used is a parallel-plane plate of 2 mm in thickness, Φ5 mm in diameter, made from Nd:YAG crystal containing 1.1 at% Nd^{3+} ions. Its input surface M_1 is dielectric coated with a reflectivity of $R_1 > 99.8\%$ at the lasing wavelength of $\lambda = 1.064$ μm, but with antireflective coating at the pumping wavelength of $\lambda = 808$ nm. The other surface is coated with high transmission of 99.9% at the lasing wavelength. The laser cavity is composed of M_1 and a concave mirror M_2 which has a radius of 20 mm and reflectivity of $R_2 = 98.8\%$ at $\lambda = 1.064$ μm. A wave plate (WP) with both surfaces is coated with antireflective films and has not been inserted into the laser cavity at first. A fibre-coupled laser diode (LD) is used as a pump, whose output is focused on the laser crystal by a self-focusing lens (SL). We keep the pumping light at about 150 mW when the laser outputs single longitudinal mode with a certain linear polarization direction. Throughout the whole process, the laser works in the fundamental transverse mode state. The laser's output passes through a beamsplitter BS_1. One part (50%) is used as optical feedback and is reflected by an external feedback mirror M_{ex}. A variable attenuator (ATT) is used to set the appropriate feedback level to avoid multi feedbacks in the external cavity.[14] In laser feedback interferometers, the displacement of mirror M_{ex} is measured by calculating the intensity fringes. In our following experiments, a piezoelectric transducer (PZT) that drives the mirror M_{ex} is used to mimic the displacement. Its motion varies the phase of the feedback light and then the laser intensity is modulated. Mirror M_{ex} is placed on a translation stage so that we can adjust its distance to the laser cavity, which we refer to the initial external cavity length L_{ext}. The other output is then divided by BS_2. With one beam, we detect the laser's total intensity modulation with a photodetector D. A Wollaston prism W divides the other beam into two orthogonal directions, and their intensities are detected by photodetectors D_1 and D_2, respectively.

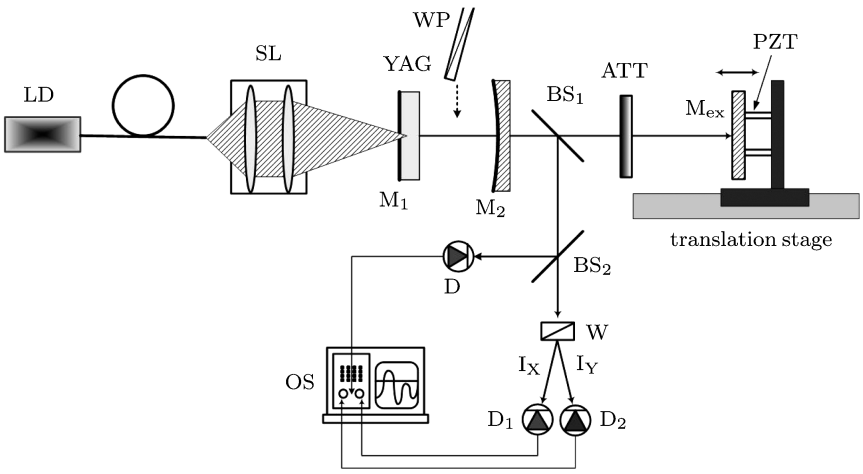


Fig. 1. Diode pumped microchip Nd:YAG laser with optical feedback.

3. Experimental results

The Nd:YAG lasers, which are almost optically isotropic, may operate on more than one polarization mode. Research[15,16] shows that two orthogonal linearly polarized eigenstates exist for each longitudinal mode order. However, the laser usually outputs single polarization mainly due to the strong competition between orthogonal polarizations and the difference of their threshold gain, which results from crystal residual stress, inhomogeneity of the gain medium and optical thin-film, and so on. This means that in the spatially monomode case the laser is also monomode in

polarization but bistable. Polarized feedback[17] and birefrigent feedback[18] can cause polarization flipping.

In our system, the crystal residual stress and inhomogeneity of optical thin-film have been limited to a relatively low level during the manufacturing process. Experiments show that when the intracavity anisotropy loss is small, even isotropic external cavity feedback can cause polarization switching between orthogonal linearly polarized modes, which has a negative effect to the development of laser feedback interferometers, because polarization switching changes the intensity modulation waveform and makes the fringe counting difficult.

First, without optical feedback, the microchip Nd:YAG laser outputs single longitudinal mode with a certain polarization direction. The laser cavity length L is 50 mm and nothing has been put into the inner cavity. Then the mirror M_{ex} is added to generate optical feedback and the initial external cavity length L_{ext} is set to be nearly the integral multiple of the cavity length (about 200 mm). On this occasion, we apply the triangular scanning voltage to the PZT and move the mirror M_{ex} within micron dimension. The laser intensity modulation is shown in Fig. 2. The phase of external feedback is given by $\phi_{ext}(= 4\pi L_{ext}/\lambda)$. As we can see, one period of intensity fluctuation occurs when the external cavity length changes $\lambda/2$. However, the total light intensity waveform does not look like a cosine wave as reported but more like a full-wave rectification. Using the polarizing beamsplitter, we find that the total light intensity consists of two orthogonal linear polarized modes, which we refer to the "o-light" and "e-light". The o-light and e-light

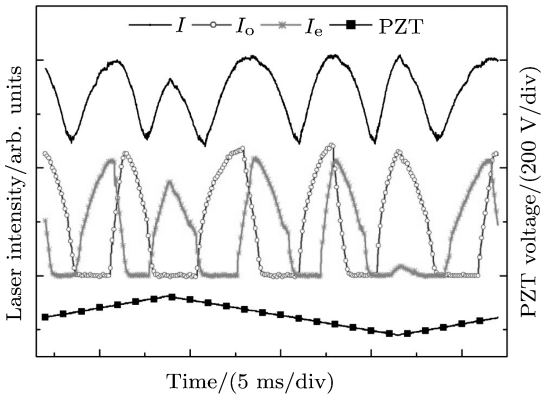


Fig. 2. Intensity modulation curves of the total light and the two orthogonal polarized modes, when the initial external cavity length L_{ext} is the integral multiple of the cavity length.

both are linearly polarized light but in orthogonal directions. Both of them are modulated by the external cavity length; because of the strong intermode competition, when one mode begins to oscillate, the other will extinguish quickly. They switch alternately and each oscillates half of a period.

We then study the influence of the initial external cavity length. We use the translation stage to change the initial external cavity length. The L_{ext} is now about $(m+1/2)L$ (225 mm), where m is an integer. The phenomenon called "mode hopping" occurs, which we have described in detail in Ref. [19], as shown in Fig. 3. On this occasion, the laser switches its oscillation between two adjacent longitudinal modes (N mode and $N+1$ mode). The total light intensity waveform looks like a full-wave rectification and the fluctuation period has been shortened to $\lambda/4$. However, the total light intensity curve we got is little different from that in Ref. [19]. It is not as smooth as the previously reported curves. Using the polarizing beamsplitter, we find that the total light intensity also consists of two orthogonal linearly polarized lights. Polarization switching occurs whether the N mode or the $N+1$ mode is oscillating. The total light intensity is actually the mixing of "mode hopping" and "polarization switching". The polarization switching is independent of the initial external cavity length.

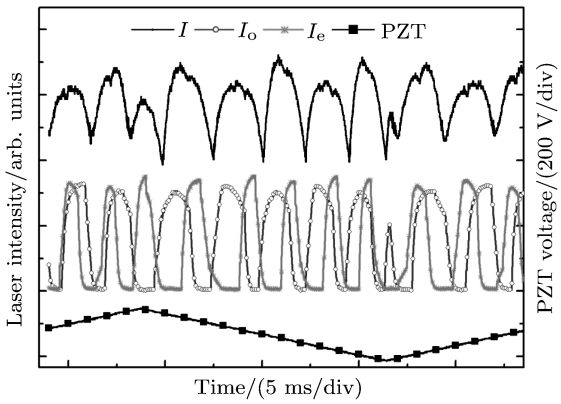


Fig. 3. Intensity modulation curves of the total light and the two orthogonal polarized modes, when L_{ext} is the integral multiple and a half of the intra-cavity length.

After that, we insert a tilted waveplate into the laser inner cavity, which obviously increases the intracavity anisotropy loss and enlarges the difference between the threshold gains of the two orthogonal eigenstates. For example, when the threshold gain of the o-light is much smaller than that of the e-light and the feedback effect could not compensate that, the e-light will be suppressed during the whole process. The intensity modulation curves are obtained when

$L_{\rm ext} = mL$ and $L_{\rm ext} = (m+1/2)L$, as shown in Figs. 4 and 5. When $L_{\rm ext} = mL$, the waveform looks like cosine wave and the fluctuation period is $\lambda/2$; when $L_{\rm ext} = (m + 1/2)L$, the waveform looks like full-wave rectification and is quite smooth, the fluctuation period is $\lambda/4$. No polarization switching is found on either occasion and the curves are the same as the previously reported ones. Note that the waveplate is not required, a glass plate or a polarizer with both surfaces coated by antireflective films is also appropriate. We use the waveplate just because it is the only optical element we have at hand with both surfaces coated by antireflective films at the lasing wavelength of 1064 nm.

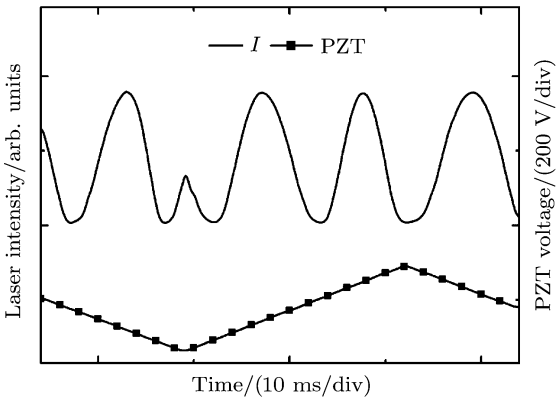


Fig. 4. Intensity modulation waveform, when $L_{\rm ext} = mL$.

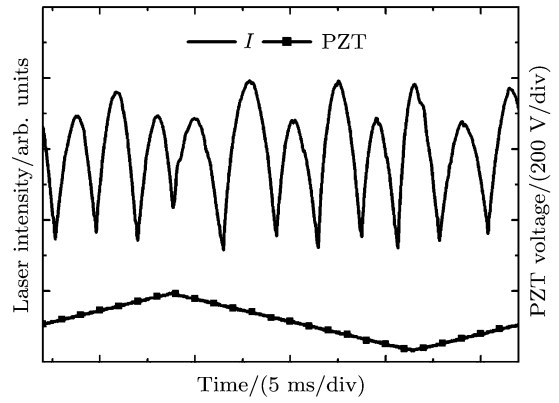


Fig. 5. Intensity modulation waveform, when $L_{\rm ext} = (m + 1/2)L$.

4. Theoretical analysis

According to the self-consistency of standing wave cavity, the intensity modulation mechanism of optical feedback has been considered as the modulation of the threshold gain of a laser.[20,21]

The initial electric vector $E_0(t)$ exiting from output surface of the Nd:YAG laser travels a round trip in the laser active cavity and the external feedback cavity, respectively. After the round trips, $E_0(t)$ turns into the final electric vector $E(t)$, which can be written as

$$E(t) = r_1 r_2 \exp\left(j4\pi\nu\frac{nd}{c} + 2gd\right)E_0(t) + r_1 T_2 r_3 \xi \exp\left(j4\pi\nu\frac{nd + L_{\rm ext}}{c} + 2gd\right)E_0(t), \quad (1)$$

where r_1 and r_2 are the amplitude reflection coefficients of M_1 and M_2, $T_2 = 1 - r_2^2$ is the transmission coefficient of M_2, r_3 is the amplitude reflection coefficient of the external feedback mirror $M_{\rm ex}$, ξ is the feedback ratio of the external optical field coupled into the laser cavity, $L_{\rm ext}$ is the external cavity length, n is the effective refractive index of the laser cavity material, d is the length of gain medium, and g is the linear gain per unit length due to the stimulated emission inside the laser cavity in the presence of feedback.

According to the laser equilibrium requirement $E(t) = E_0(t)$, the following equation can be obtained:

$$r_1 r_2 \exp\left(j4\pi\nu\frac{nd}{c} + 2gd\right) \times \left[1 + \beta\exp\left(j4\pi\nu\frac{L_{\rm ext}}{c}\right)\right] = 1, \quad (2)$$

where $\beta = T_2 r_3 \xi / r_2$. From Eq. (2), the reinjected light will cause a change to the threshold gain of the laser as follows:

$$\Delta g = -\frac{\beta}{2nd}\cos\left(4\pi\nu\frac{L_{\rm ext}}{c}\right). \quad (3)$$

The laser intensity modulation can be expressed as

$$\Delta I = I_0 k \Delta g = \varsigma\cos(\phi_{\rm ext}), \quad (4)$$

where k is a constant relating to the laser operation parameters, $\phi_{\rm ext} = 4\pi\nu L_{\rm ext}/c$, $\zeta = \beta k I_0/2nd$. And I_0 is the initial laser intensity without optical feedback. From Eq. (4), we can see that the laser intensity modulation with the isotropic external feedback is in the form of a cosine waveform, whose period corresponds to half wavelength ($\lambda/2$) variation of the external cavity length. The simulated intensity modulation curve is presented in Fig. 6, which is in good agreement with the experimental result shown in Fig. 4.

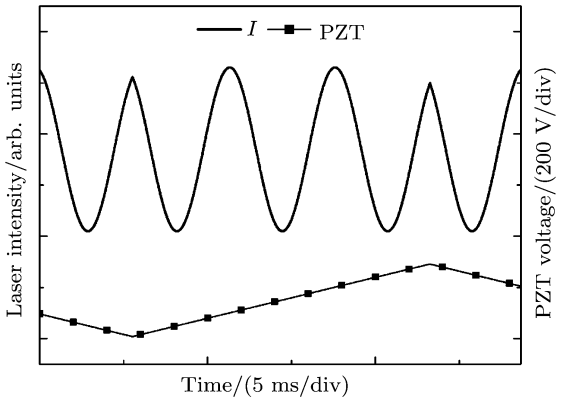


Fig. 6. Simulation of laser intensity modulation curve with external optical feedback.

Then we take the two orthogonal eigenstates into account (we refer them to the o-light and e-light). Microchip Nd:YAG lasers have been reported to output orthogonal polarization modes when the pump is strong. There exist two orthogonal eigenstates for each longitudinal mode order, though usually one polarization is suppressed by the other. Research shows that the Nd:YAG chip's residual birefringence causes a frequency difference between orthogonal polarization modes.[15] Equation (4) can be expressed as follows:

$$\begin{cases} \Delta I_{\rm o} = \varsigma_{\rm o} \cos\left(\dfrac{4\pi}{c}\nu_{\rm o} L_{\rm ext}\right), \\ \Delta I_{\rm e} = \varsigma_{\rm e} \cos\left(\dfrac{4\pi}{c}\nu_{\rm e} L_{\rm ext}\right), \end{cases} \tag{5}$$

where $\varsigma_{\rm o}$ and $\varsigma_{\rm e}$ are constants corresponding to o-light and e-light, respectively. $\nu_{\rm o}$ and $\nu_{\rm e}$ are the optical frequencies of o-light and e-light respectively. From Eq. (5), we can find that both of the two orthogonal eigenstates vary one period when the length of external cavity changes half wavelength. However, there is a phase difference $\delta = (4\pi/c)\Delta\nu L_{\rm ext}$ between $\Delta I_{\rm o}$ and $\Delta I_{\rm e}$. The feedback-induced loss modulation is non-synchronous for the two orthogonal polarizations. In fact, in our experiments, the two eigenstates are of the same longitudinal mode and share the same inverted population. Figures 2 and 3 reveal that there is a strong mode competition between them, which must be considered. Thus, only one mode can oscillate at one moment, i.e., when one mode starts to oscillate the other one will be extinguished. When feedback causes a negative effect to one polarization and makes its threshold gain larger than that of the other, the other polarization may then use the inverted population and start oscillation. The intensity modulation of the two orthogonal linearly polarized eigenstates can be expressed as

$$\Delta I = \begin{cases} \Delta I_{\rm o} = \varsigma_{\rm o} \cos\left(\dfrac{4\pi}{c}\nu_{\rm o} L_{\rm ext}\right), & \text{if } \ g_{\rm o} \le g_{\rm e}, \\ \Delta I_{\rm e} = \varsigma_{\rm e} \cos\left(\dfrac{4\pi}{c}\nu_{\rm o} L_{\rm ext} + \delta\right), & \text{if } \ g_{\rm e} \le g_{\rm o}. \end{cases} \tag{6}$$

We can also estimate the value of δ, $\delta = 2\pi(L_{\rm ext}/L)(\Delta\nu)/(\Delta)$, where Δ is the longitudinal mode spacing of the laser and is about 3 GHz in our system. And $\Delta\nu$ is usually several tens of MHz.[16] Hence, as we can see, the Δ is so large that small change of the initial external cavity length $L_{\rm ext}$ will exert little influence on δ, which explains that the polarization switching is independent of the initial external cavity length. When $L_{\rm ext} = 4L$ (as in our system), supposing $\Delta\nu = 60$ MHz, then we find that δ is about $\frac{1}{6}\pi$.

Based on the considerations above, the simulated intensity modulation curves are presented in Fig. 7, which are in good agreement with Fig. 2. Note that in the simulation, we assume that polarization switching needs no time. However, the real transition is much slower. And we also assume that the peak intensity of o-light is a bit larger than that of e-light, because the o-light is the initial lasing mode and has lower threshold gain. The theory and simulations of "mode hopping" has been described in Ref. [19] and will not be presented here.

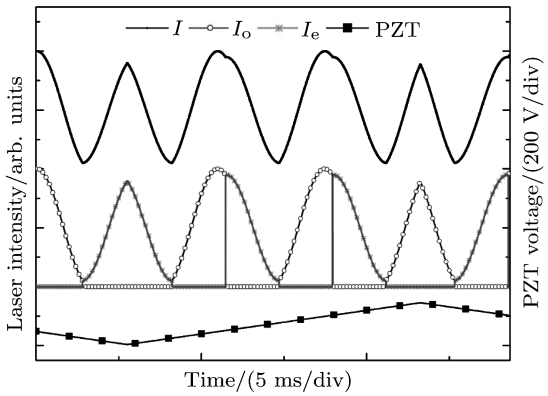


Fig. 7. Simulation of laser intensity modulation curves with external optical feedback, when polarization switching is considered.

5. Conclusions

In this paper, we have systematically studied polarization switching in quasi-isotropic microchip Nd:YAG lasers induced by optical feedback. Our results show that when the intracavity anisotropy loss, caused by the inhomogeneity of optical film, residual

stress and phase retardation of optical elements, is small, external optical feedback can cause polarization switching between two orthogonal polarization eigenstates of one laser longitudinal mode, which leads to the distortion of laser intensity modulation waveform. By inserting a tilted waveplate into the inner laser cavity to increase the intracavity anisotropy loss, one polarization mode can be suppressed and the laser works in single-polarization state.

Microchip lasers based on optical feedback are widely used in practical applications of imaging, sensing and metrology. For these applications, steady laser intensity modulation waveforms are required. Our results show that if we increase the intracavity anisotropy loss, the laser can steadily work on single-polarization with good wave shape. Meanwhile, a possible method can be used to improve the measuring resolution. According to the result shown in Fig. 3, we can improve the $\lambda/2$ resolution of conventional feedback measument to $\lambda/8$ by detecting the polarization switching points.

References

[1] King P G R and Steward G J 1963 *New Sci.* **17** 180
[2] Shinohara S, Mochizuki A, Yoshida H and Sumi M 1986 *Appl. Opt.* **25** 1417
[3] Kawai R, Asakawa Y and Otsuka K 1999 *IEEE Photon. Technol. Lett.* **11** 706
[4] Giulian G, Norgia M, Donati S and Bosch T 2002 *J. Opt.* A: *Pure Appl. Opt.* **4** S283
[5] Zhou L F, Zhang B, Zhang S L, Tan Y D and Liu W X 2009 *Chin. Phys.* B **18** 1141
[6] Gouaux F, Servagent N and Bosch T 1998 *Appl. Opt.* **37** 6684
[7] Ren C and Zhang S L 2009 *Acta Phys. Sin.* **58** 3558 (in Chinese)
[8] Wang M and Lai G 2004 *Opt. Commun.* **238** 237
[9] Lu C, Wang J and Deng K 1995 *Appl. Phys. Lett.* **66** 2022
[10] Castellini P, Revel G M and Tomasini E P 1998 *Shock Vib. Dig.* **30** 443
[11] Giuliani G, Bozzi-Pietra S and Donati S 2003 *Meas. Sci. Technol.* **14** 24
[12] Otsuka K and Abe K 1999 *Opt. Lett.* **24** 1862
[13] Wan X J, Duo L and Zhang S L 2007 *Opt. Lett.* **32** 367
[14] Cui L, Zhang S L and Wan X J 2008 *Chin. Phys.* B **17** 644
[15] Owyoung A and Esherick P 1987 *Opt. Lett.* **12** 999
[16] Fei L G, Li Y, Zong X B and Zhang S L 2005 *Opt. Commun.* **249** 255
[17] Besnard P, Jia X, Dalgliesh R and May A D 1993 *J. Opt. Soc. Am.* B **10** 1605
[18] Fei L G, Zhang S L and Wan X J 2004 *Chin. Phys. Lett.* **21** 1944
[19] Tan Y D, Zhang S L, Wan X J and Cheng X 2006 *Chin. Phys.* **15** 2934
[20] Bearden A, O'Neill M P, Osborne L C and Wong T L 1993 *Opt. Lett.* **18** 238
[21] Wang W M, Boyle W J O, Grattan K T V and Palmer A W 1993 *Appl. Opt.* **32** 1551