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Mode hopping in single-mode microchip Nd:YAG lasers induced by optical feedback*

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The mode hopping phenomenon induced by optical feedback in single-mode microchip Nd:YAG lasers is presented. With optical feedback, mode hopping strongly depends on two factors: the ratio of external cavity length to intra-cavity length, and initial gains of the two hopping modes. When external cavity length equals an integral multiple of intra-cavity length, there is almost no mode hopping. However, if the external cavity length does not equal an integral multiple of intra-cavity length, mode hopping occurs. The ratio of external cavity length to intra-cavity length determines the position of two-mode hopping. The initial gains of the two hopping modes determine the corresponding peak values and oscillating periods of them in the intensity modulation curves.

Keywords: mode hopping, optical feedback, modes competition, intensity modulation

PACC: 4210J, 4255R

1. Introduction

Mode hopping in external cavity semiconductor lasers has been studied widely.[1−5] Lang and Kobayashi reported that the light–current characteristics showed hysteresis effects of mode hopping in the presence of optical feedback.[1] Low-frequency optical noise induced by mode hoping was studied by Biesterbos *et al*.[2] Sciamanna *et al* proposed the polarization mode-hopping in single-mode vertical-cavity surface-emitting lasers with optical feedback.[3,4] Cheng *et al* investigated the suppression of mode hopping in diode lasers by orthogonal-polarization optical feedback.[5] All the above researches indicate that mode hopping influences the intensity modulation, optical noise and longitudinal mode output and so on. Since diode-pumped microchip lasers based on feedback are widely used in practical applications such as imaging,[6,7] laser Doppler velocimetry,[8−10] or vibrometry,[11] it is crucial to study the mode hopping induced by optical feedback for microchip lasers. However, to the best of our knowledge, little is known nowadays about the case of microchip lasers.

In this paper, mode hopping in single-mode microchip Nd:YAG lasers induced by optical feedback is systematically studied. With the feedback loop on, threshold gain of two adjacent modes (N mode and $N+1$ mode, represents lasing mode, non-lasing mode, respectively) are both modulated by external cavity length, and $\lambda/2$ change of external cavity length makes them both undulate one period. Due to the mode competition between these two adjacent modes with the same polarization, if the gain of N mode is lower than $N+1$ mode, the laser switches its oscillation frequency to the $N+1$ mode, which is called mode hopping. It strongly depends on the ratio of external cavity length to intra-cavity length, initial positions of the N mode and $N+1$ mode in the gain curve. If external cavity length equals an integral multiple of intra-cavity length, there is nearly no mode hopping and the intensity curves are sine waves. Otherwise, mode hopping occurs. In particular, if the external cavity length equals an integral multiple and a half of intra-cavity length, the intensity curves are similar to full-wave rectification. The ratio of external cavity length to intra-cavity length determines the position of the two-mode hopping. While the initial positions of the two hopping modes in the gain curve determine the duty ratio of them in a period of intensity modulation curve.

2. Experimental setup

Experiments are carried out on a diode-pumped half-intracavity Nd:YAG laser, with the experimental

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setup shown in Fig.1.

The laser chip used consists of parallel-plane plate of 2 mm thickness, Φ5 mm diameter, made of YAG crystal containing 1.1 at % Nd^{3+} ions. The pumping surface is dielectric-coated to a reflectivity of $r_1 = 100\%$ at the lasing wavelength of $\lambda = 1.064\,\mu$m, but antireflective at the pumping wavelength of $\lambda = 808$ nm. The other surface is coated with high transmissivity of 99.9% at the lasing wavelength. The laser cavity with a cavity length l about 54 mm is composed of the pumping surface of YAG and a concave mirror M which has a radius of 200 mm and reflectivity of $r_2 = 98.8\%$ at $\lambda = 1.064\,\mu$m. The pump is a fibre-coupled laser diode, whose output is focused on the laser crystal. We keep the pumping light at about 220 mW when the laser outputs single longitudinal mode in the absence of feedback. Throughout the whole process, the laser works in the fundamental transverse mode state. M_E is external reflective mirror with the amplitude reflectivity of $r_3 = 80\%$, used to reflect beams back into laser. Both M_E and M form the feedback external cavity, whose length is L. PZT_1 and PZT_2 are used to modify the laser cavity length and the external cavity length, respectively. The laser modes are observed by F-P, of which the free spectral range (FSR) is 3.98 GHz. D can be used to detect the output intensity.

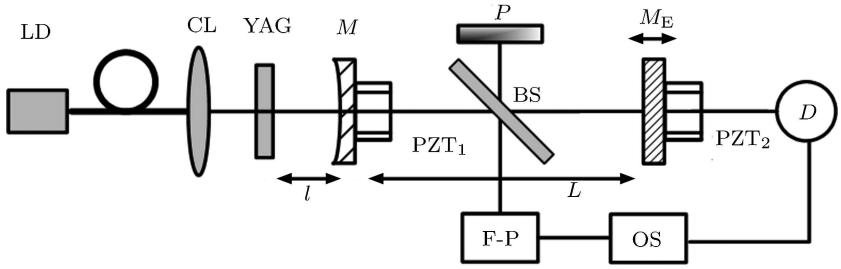


Fig.1. Experimental setup. M, M_E: mirrors; P: polarizer; BS: beam splitter; $PZT_{1,2}$: piezoelectric transducer; YAG: YAG crystal; CL: collimate lens; LD: laser diode; F-P: Fabry–Perot scanning interferometer; OS: oscilloscope. D: photoelectronic detector.

3. Experimental results

First of all, a set of experiments are carried out to compare the intensity modulation and longitudinal mode under the different situations: (a) without feedback; (b) weak feedback; (c) higher feedback. The results are shown in Fig.2.

Figure 2 (a) shows, in the absence of optical feedback, that the output intensity is smooth, without any undulation, and the laser works on single mode (N mode), which is observed by F-P scanning interferometer with a FSR of 3.98 GHz. With weak feedback ($< 1\%$), there is no mode hopping, and the output intensity looks like a sine waveform,[12] as shown in Fig.2(b). In the presence of higher feedback (approximately 16% in our experiments), the laser hops between the lasing mode (Nmode) and non-lasing mode ($N+1$ mode), and the output intensity is no longer similar to sine wave, as shown in Fig.2(c). In fact, the N mode and $N+1$ mode do not oscillate at the same time, i.e. one mode starts to oscillate accompanying the extinguishing of the other mode.

As we mentioned in the introduction, two factors play an important role on the mode hopping phenomenon: the ratio of external cavity length to intracavity length and the initial positions of the two hopping modes in the gain curve.

So we have done two kinds of experiments, as described next. The first one is to change the ratio of external cavity length to intra-cavity length. In the second experiment, we change the positions of the two hopping modes in the gain curve by tuning the intracavity length.

Firstly, the influence of external cavity length on mode hopping is considered. We connect the feedback loop and make sure that M_E is aligned perfectly. Then, we drive PZT_2 with a triangular wave to make mirror M_E periodically tune the external cavity length, and the intensity modulation can be observed just like that in Fig.2(c). For the convenience of observation, we tune the intra-cavity length by driving PZT_1 until the peak value of N mode is equal to that of $N+1$ mode, and then, stop changing the intracavity length. The experimental results are shown in Fig.3.

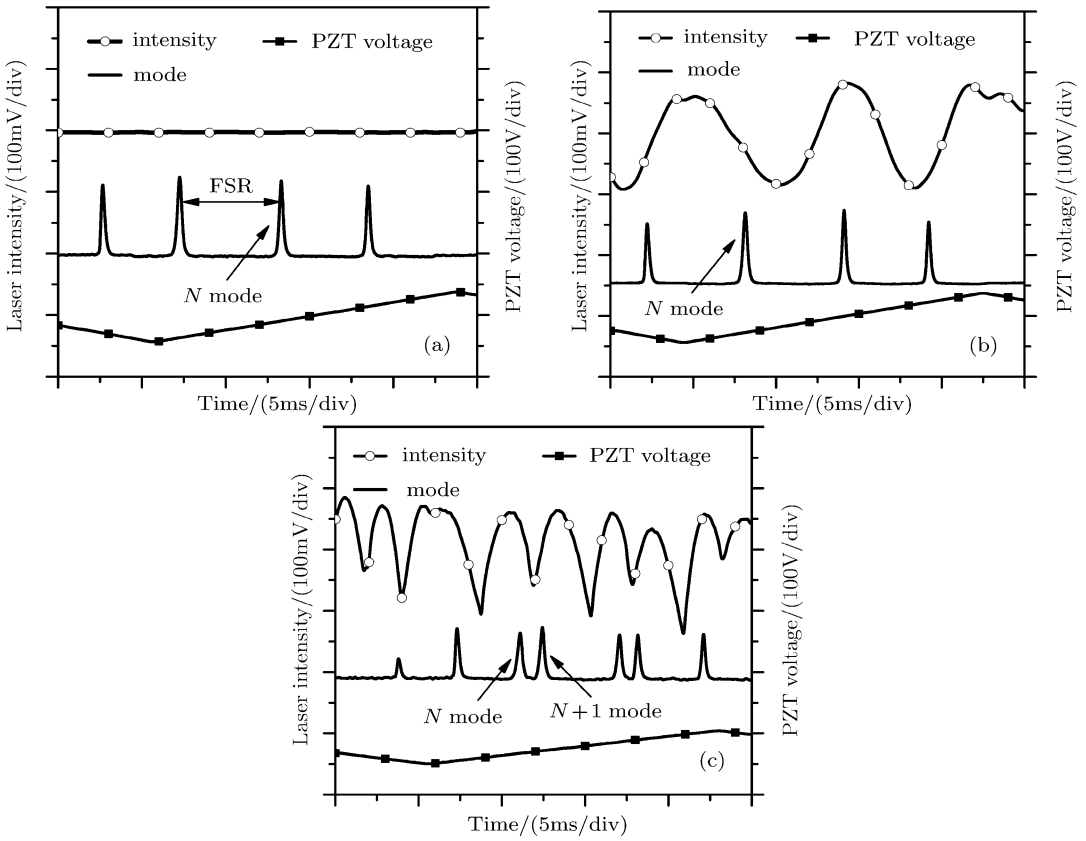


Fig.2. Oscilloscope waveforms of intensity modulation curves and longitudinal mode distributions with different situations: (a) no feedback; (b) weak feedback; (c) higher feedback.

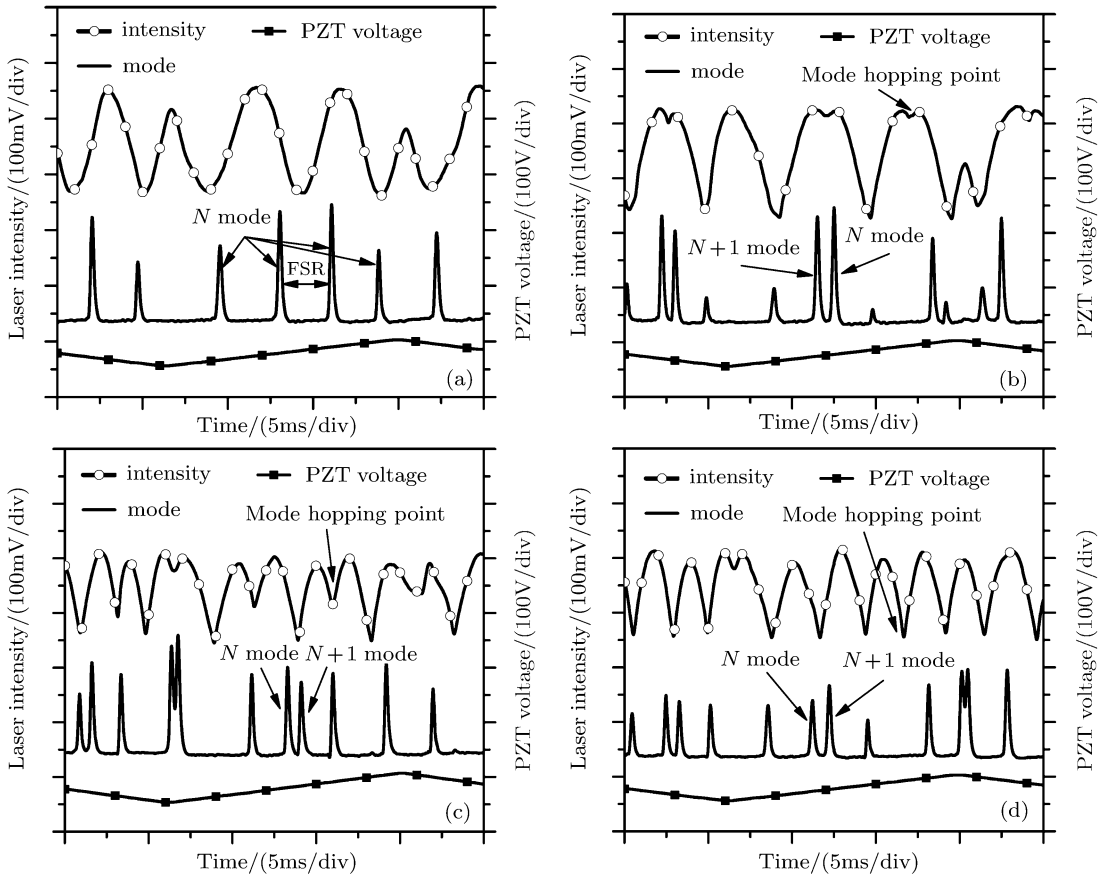


Fig.3. Oscilloscope waveforms of intensity modulation curves and longitudinal mode distributions at different external cavity lengths: (a) $L = 322\,\mathrm{mm}$; (b) $L = 336\,\mathrm{mm}$; (c) $L = 342\,\mathrm{mm}$; (d) $L = 350\,\mathrm{mm}$.

Figure 3(a) shows that there is no mode hopping and the waveform looks like a sine waveform when the external cavity length (322 mm) approximately equals an integral multiple of the intra-cavity length (54 mm). Then, we make the external cavity length equal to 336, 342 and 350 mm. Observation of the mode hopping is successful. Mode hoping here specifically means that the two adjacent modes (N and $N+1$ modes) hop from each other in a period of feedback curve, which can be called mode hoping in feedback period. Due to mode hopping in the feedback period, there is also mode hopping from one feedback period to the other one adjacent. Figures 3(b)–(d) show that when the external cavity length changes, the positions of mode hopping point in the intensity modulation curves move down. In particular, when the external cavity length (350 mm) approximately equals an integral multiple and a half of the intra-cavity length (54 mm), mode hopping point moves to the lowest point in the intensity modulation curve, which looks like a full-wave rectification, as shown in Fig.3(d). Although the position of mode hopping point changes accompanying the variation of external cavity length, the two hopping modes share the feedback period equally, i.e., the oscillating period of each mode equals half of feedback period. If we continue to change the external cavity length, the intensity modulation curves will repeat the figurations shown in Fig.3. Hence, we can conclude that the ratio of external cavity length to intra-cavity length determines the occurrence and position of mode hopping.

In the second experiment, for the convenience of observation, the external cavity length is kept at 350 mm. Then, we tune the intra-cavity length to change the initial positions of the two hopping modes in the gain curve by driving the PZT_1, i.e. change the initial gains of the two hopping modes. Three conditions are considered: (a) N mode and $N+1$ mode are located symmetrically in the gain curve, i.e. the initial gains of the two modes are equal; (b) $N+1$ mode is closer to the gain curve centre than N mode, i.e. the initial gain of N mode is smaller than that of $N+1$ mode; (c) and (d) N mode is closer to the gain curve centre than $N+1$ mode, i.e. the initial gain of N mode is bigger than that of $N+1$ mode. The results are shown in Fig.4.

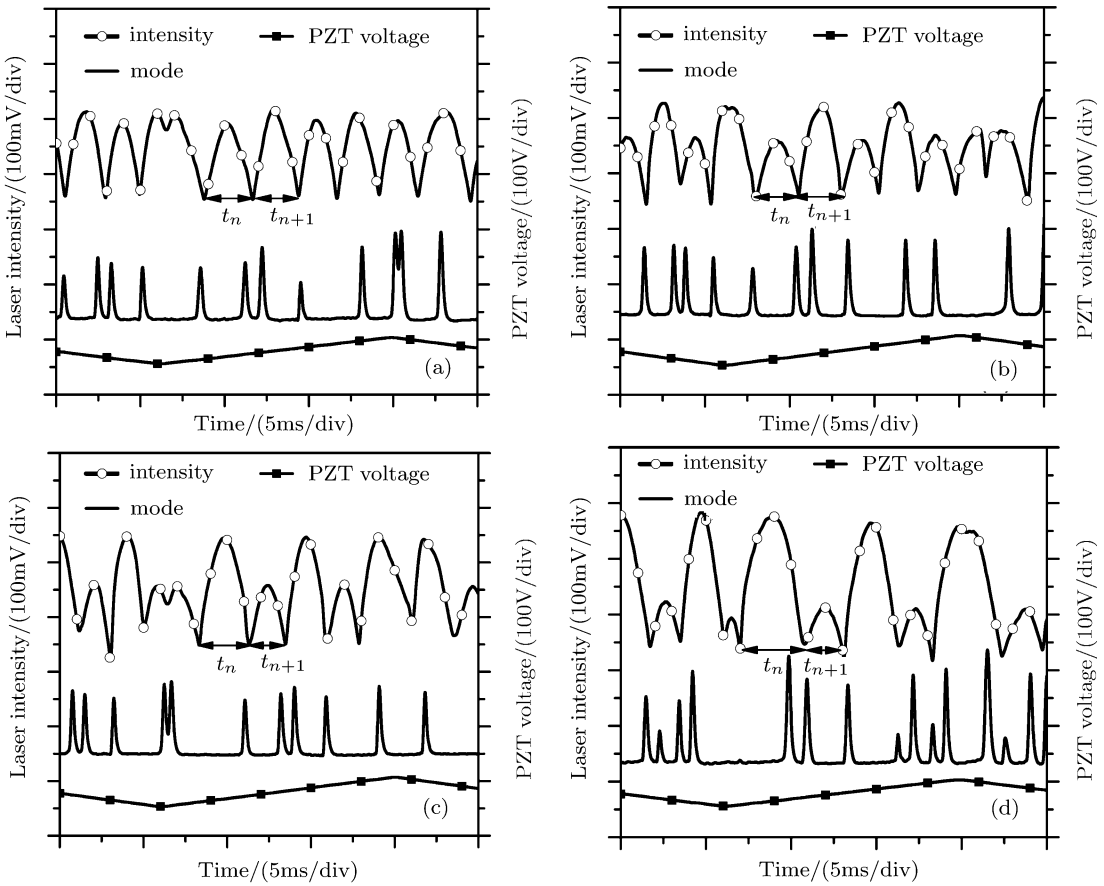


Fig.4. Oscilloscope waveforms of intensity modulation curves and longitudinal mode distributions: (a) N mode's initial gain is equal to $N+1$ mode's; (b) N mode's initial gain is smaller than $N+1$ mode's; (c) and (d) N mode's initial gain is bigger than $N+1$ mode's.

In Fig.4, t_n and t_{n+1} represent the oscillating periods of N mode and $N+1$ mode, respectively. Figure 4 (a) shows the results we have discussed in Fig.3. When N mode's initial gain is equal to $N+1$ mode's, they share the feedback period equally, i.e. $t_n = t_{n+1}$, which is equal to half of feedback period. If N mode's initial gain is smaller than $N+1$ mode's, the oscillating period of N mode t_n is smaller than that of $N+1$ mode t_{n+1}, as shown in Fig.4(b). In contrast, if N mode's initial gain is bigger than $N+1$ mode's gain, the oscillating period of N mode t_n is larger than that of $N+1$ mode t_{n+1}, as shown in Figs.4(c) and (d). For peak values of the two modes, there are similar conclusions. So we can conclude that the initial gains of the two hopping modes determine the corresponding oscillating periods (t_n and t_{n+1}) and peak values in the intensity modulation curve.

We have also carried out the above experiments with different external cavity lengths, and obtain similar results and conclusions.

4. Theoretical analysis

In the presence of feedback, according to self-consistency theory of standing wave cavity, the reinjected light will cause a change to the threshold gain of the laser as follows[12,13]

$$\Delta g = g - g_0 = -\frac{\xi}{l}\cos(\omega\tau), \tag{1}$$

where g and g_0 are the laser threshold gains with and without optical feedback respectively, ξ is a constant proportional to the reflectivity of external feedback mirror, l is the laser intra-cavity length, ω is the laser cavity frequency, $\tau = \dfrac{2L}{c}$ represents the laser round-trip time in external cavity, L is external cavity length, and c is light velocity in vacuum.

For the two adjacent longitudinal modes, Eq.(1) can be expressed as follows:

$$\begin{aligned} g_N &= \Delta g_N + g_{(N)0} = g_{(N)0} - \frac{\xi}{l}\cos(\omega_N\tau), \\ g_{N+1} &= \Delta g_{N+1} + g_{(N+1)0} = g_{(N+1)0} - \frac{\xi}{l}\cos(\omega_{N+1}\tau). \end{aligned} \tag{2}$$

For the two adjacent longitudinal modes, we can get

$$\omega_{N+1} - \omega_N = 2\pi\frac{c}{2l}. \tag{3}$$

The laser intensity with optical feedback can be expressed as[12,14,15]

$$I = I_0(1 - k\Delta g), \tag{4}$$

where k is a constant, I_0 is the laser initial intensity corresponding to the initial gain.

Substituting Eqs.(2) and (3) into Eq.(4), the intensity modulation of the two adjacent longitudinal modes with optical feedback can be expressed respectively as

$$I = \begin{cases} I_N = I_{0N}\left[1 + k\dfrac{\zeta}{l}\cos\left(\dfrac{2}{c}\omega_N L\right)\right], & \text{if } g_N \geq g_{N+1}, \quad (5a) \\ I_{N+1} = I_{0(N+1)}\left[1 + k\dfrac{\zeta}{l}\cos\left(\dfrac{2}{c}\omega_N L + 2\pi\dfrac{L}{l}\right)\right], & \text{if } g_{N+1} \geq g_N. \quad (5b) \end{cases}$$

In fact, in our experiments, the two hopping modes are of the same polarization. Figures (3) and (4) reveal that there is strong mode competition between them in the mode hopping, which is the same as those reported by Lang and Kobayashi [1] and by Biesterbos *et al.*[2] Thus, only one mode can oscillate at some moment, i.e., when one mode starts to oscillate, the other one will be extinguished. When the external cavity length is changed by the action of PZT_2, both g_N and g_{N+1} are tuned like a cosine waveform, expressed by Eq.(2). Suppose N mode is the lasing mode at first. Thus, for $g_N > g_{N+1}$ at the beginning,

the output intensity I is given by Eq.(5a). N mode keeps oscillating until $g_N = g_{N+1}$, then at this point, which we call mode hopping point, mode hopping occurs between the two adjacent modes. So $N+1$ mode becomes the lasing mode and N mode extinguishes, then we have $g_N > g_{N+1}$. The output intensity I is given by Eq.(5b). Suppose $N+1$ mode keeps oscillating until $g_{N+1} = g_N$ again, then mode hopping occurs again. Thus, N mode becomes the lasing mode and $N+1$ mode extinguishes, and the output intensity I is given by Eq.(5a) again. Then, the above phenomena will repeat again and again as long as the external cavity length is tuned. So the whole intensity modulation curves behave according to Eq.(5).

Meanwhile, from Eq.(5), we notice that there is a phase difference δ between g_N and g_{N+1}, and also between I_N and I_{N+1}, which is determined by the ratio of external cavity length to intra-cavity length as follows:

$$\delta = 2\pi \frac{L}{l}. \tag{6}$$

The phase difference δ determines the position of $g_{N+1} = g_N$, where the two adjacent modes hop from each other. The points of $g_{N+1} = g_N$ move down with the change of phase difference δ. Thus, the mode hopping points vary with the ratio of external cavity length to intra-cavity length, just as shown in Figs.3 (b)–(d). Particularly, when $\delta = 0$, one mode suppresses the other one throughout the process. Hence, it occupies the whole feedback period and the intensity modulation curve looks like a cosine waveform. However, when $\delta = \pi$, the mode hopping point moves down to the lowest, the two hopping modes equally share the feedback period, i.e. half of feedback period, and the intensity modulation curve is similar to a full-wave rectification.

Based on the considerations above, the simulated intensity modulation curves are presented in Fig.5. Different external cavity lengths are considered: (a) $L = 324$ mm; (b) $L = 334$ mm; (c) $L = 339$ mm; (d) $L = 351$ mm. The simulation results in Fig.5 are in good agreement with the experimental results shown in Figs.3(a)–(d).

There is a slight difference between the experimental and theoretical external cavity lengths, which may be the measurement errors.

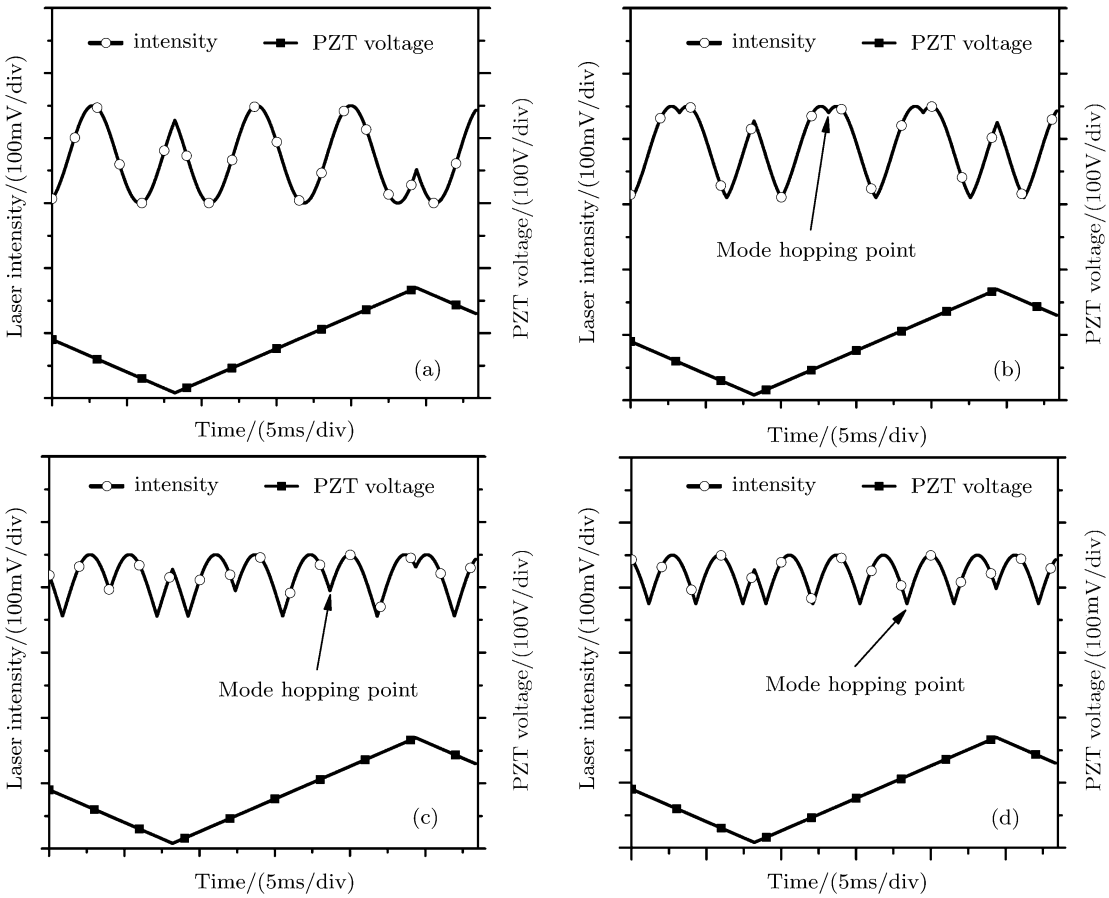


Fig.5. Simulation of intensity modulation curves with different external cavity lengths: (a) $L = 324$mm; (b) $L = 334$mm; (c) $L = 339$mm; (d) $L = 351$mm.

In the second experiment, for the convenience of observation, the external cavity length is maintained at 350 mm, so the phase difference δ is π. When the initial positions of the two hopping modes in the gain curve are different, the initial gains g_{N0} and $g_{(N+1)0}$ are different, which results in different I_{N0} and $I_{(N+1)0}$. Hence, the peak values of I_N and I_{N+1} are different. Meanwhile, due to the different initial gains g_{N0} and $g_{(N+1)0}$, the smaller one is suppressed by the bigger one, the corresponding oscillating period is smaller too. Based on the consideration of modes competition between the two adjacent modes, the different initial gains g_{N0} and $g_{(N+1)0}$ will cause both the different oscillating periods and peak values in the intensity modulation curves. The simulated intensity modulation curves of two-mode hopping are shown in Fig.6, which are in good agreement with the experimental results in Figs.4(a) – (d).

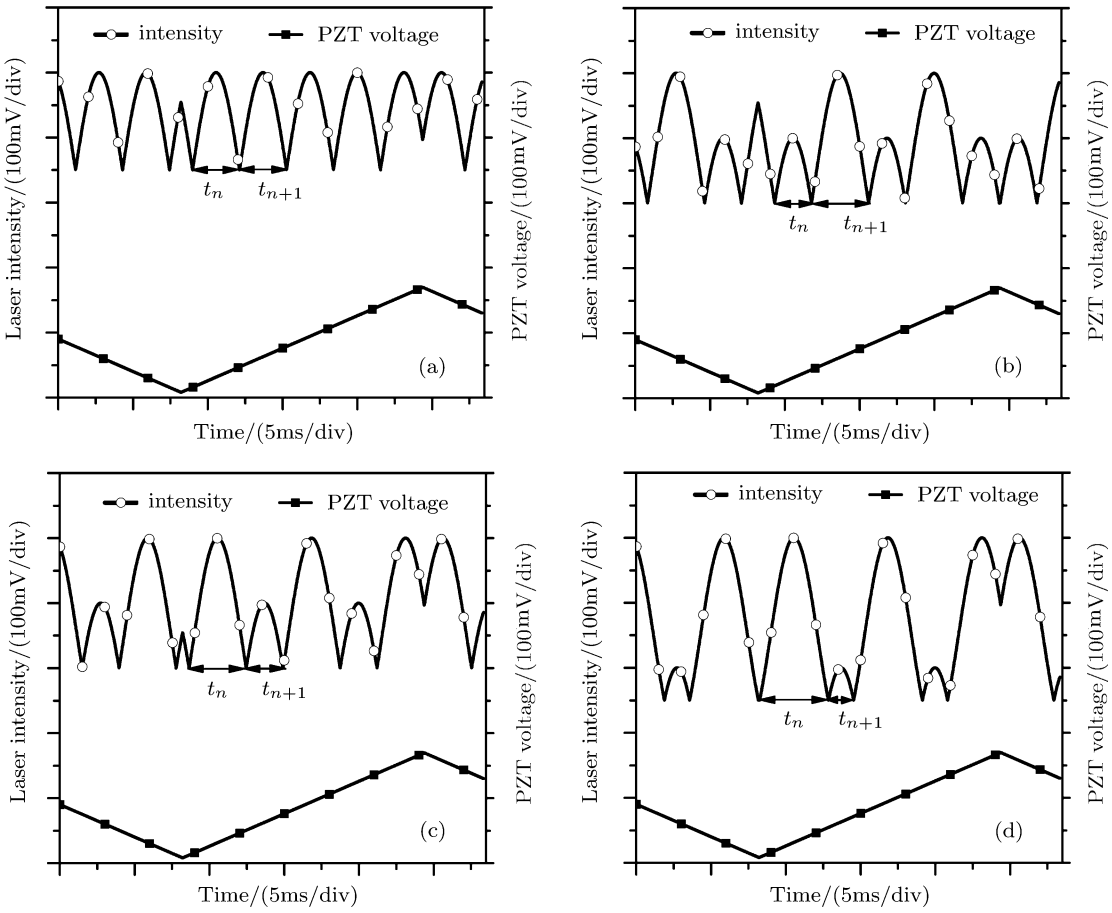


Fig.6. Simulation of intensity modulation curves with different initial gains for the two hopping modes: (a) N mode's initial gain is equal to $N+1$ mode's; (b) N mode's initial gain is smaller than $N+1$ mode's; (c) and (d) N mode's initial gain is bigger than $N+1$ mode's.

5. Conclusions

In this paper, we have systematically studied mode hopping in single-mode Nd:YAG laser induced by optical feedback. Two factors which play an important role in mode hopping are presented. One is the ratio of external cavity length to intra-cavity length, which determines whether the mode hopping can occur and the position of the two-mode hopping. The other is the initial gains of the two hopping modes, which determine the peak values and oscillating periods of the two hopping modes in the intensity modulation curve.

Microchip lasers based on optical feedback are widely used in practical applications of imaging, sensing, and metrology. For these applications, steady single-mode lasers are required. Our results can be used to suppress mode hopping. If we make the ratio

of external cavity length to intra-cavity length be an integral, the laser can steadily work on single-mode without any mode hopping even at a high pump level. Meanwhile, a possible method can be used in measurement. We set the two hopping modes with equal initial gains, according to the results shown in Fig.3, the two hopping modes equally share the half of a feedback period. Thus, we can improve the $\lambda/2$ resolution of conventional feedback measurement to $\lambda/4$ by detecting the mode hopping points.

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