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Generation of self-oscillations from a singly resonant periodically poled potassium titanyl phosphate crystal frequency doubler*

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We report on the generation of self-oscillations from a continuously pumped singly resonant frequency doubler based on a periodically poled potassium titanyl phosphate crystal (PPKTP). The sustained square-wave and staircase curve of self-oscillations are obtained when the incident pump powers are below and above the threshold of subharmonic-pumped parametric oscillation (SPO), respectively. The self-oscillations can be explained by the competition between the phase shifts induced by cascading nonlinearity and thermal effect, and the influence of fundamental nonlinear phase shift by the generation of SPO. The simulation results are in good agreement with the experiment data.

Keywords: self-oscillations, singly resonant frequency doubler, phase shift

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1. Introduction

Second harmonic generation (SHG) is an efficient way to extend the laser spectrum from the infrared to the visible region. An intracavity frequency doubling of a continuous-wave (CW) laser has been obtained with an efficiency of 95% in the condition of phase matching.[1] On the other hand, the exchange of energy between the fundamental and the harmonic fields via second-order nonlinearities occurs in the SHG under the condition of phase mismatching.[2] This kind of cascaded phenomenon can be applied to all-optical switching,[3] pulse compression,[4] femtosecond mode locking of laser,[5] noise reduction, and squeezing,[6–8] etc. Second-order cascading effects including nonlinear phase shift from a phase mismatched external cavity enhancement SHG have been studied in previous work.[6,9,10] Owing to light absorptions of the fundamental and harmonic fields in the nonlinear crystal, the strong thermal effect exists synchronously in the external nonlinear cavity. The self-oscillations will occur due to the competition between fast nonlinear phase shift and slow thermally induced refractive index change.[11] Suret *et al.*[12] observed sustained self-pulsing in a continuously pumped, triply resonant, optical parametric oscillator (OPO). Cheung *et al.*[11] obtained the optical bistability and self-oscillations from a nonlinear Fabry–Perot interferometer filled with a nematic-liquid-crystal film. Mackenzie *et al.*[13] presented the regenerative pulsations in an InSb bistable etalon, and Kong *et al.*[14] observed the optical bistability and self-oscillations in a nonlinear etalon filled with optical adhesive.

As is well known, for the experimental demonstration of the cascaded $\chi^{(2)}$ nonlinearity in a continuously pumped external cavity enhancement SHG, low cavity losses and large nonlinearity are inevitable. Fortunately, quasi-phase-matching materials have opened up possibilities for providing large nonlinearities for the nonlinear frequency conversion. With the help of a periodically poled potassium titanyl phosphate crystal (PPKTP) with which the largest nonlinearity of $d_{33} = 14.9$ pm/V can be used, we observe sustained square-wave self-oscillations when the incident pump power is below the threshold of subharmonic-pumped parametric oscillation (SPO), and sustained staircase curve self-oscillations when the incident pump power is above the threshold of SPO. The duty cycle of the self-oscillations can be controlled by the cavity length.

2. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. A singly resonant frequency doubler was pumped by a CW single frequency Nd:YVO$_4$ laser at 1.064 μm (Model F-IVB, YuGang Co., Ltd). The pump laser delivered up to 1 W of output with the stability better than ±0.5% in the given three hours. An optical isolator (OI) was used to eliminate the back reflection of the pump laser from the frequency doubler. A mode cleaner (MC) was used to improve the spatial mode and suppress the intensity noise of the pump laser. The pump intensity incident into the frequency doubler was controlled by a half wave plate (HWP1) and a polarizing beam splitter (PBS). The HWP2 was used to control the pump polarization for phase-matching in the nonlinear crystal. The incident pump beam was focused by the lens (L) on the center of the nonlinear crystal with a waist of about 46 μm. The mode matching between the pump beam and the frequency doubler

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was over 98% with the help of MC. The frequency doubler was composed of two mirrors (M1 and M2) each with a radius of curvature of 30 mm and a PPKTP crystal (Raicol Crystals). The length of the cavity was 40 mm. M1 was the input coupler with a transmission of 2% at 1.064 μm and high reflection at 532 nm ($R > 99.8\%$). M2 was the output coupler with high reflection at 1.064 μm ($R > 99.8\%$) and high transmission at 532 nm ($T > 90\%$). The PPKTP crystal had a dimension of 0.5 mm (thickness) ×2 mm (width) ×10 mm (length) with a poled period of 9 μm and both end faces antireflective coated at 1.064 μm and 532 nm ($R_{1.064\ \mu\text{m},532\ \text{nm}} < 0.25\%$), and was temperature controlled by a temperature controller with an accuracy of ±0.01 °C (Model YG-4S, YuGang Co., Ltd). The length of the frequency doubler was controlled by a piezoelectric transducer (PZT) that was driven by a high voltage amplifier (Model YG-2009A, YuGang Co., Ltd). A dichroic beam splitter (DBS) was used to separate the fundamental beam from the second harmonic (SH) beam. The SH output was measured by a power meter (PM). The transmitted fundamental intensity was measured by an InGaAs photon detector (PD) and recorded by an oscilloscope (Tektronics TDS 2024).

When the frequency doubler was locked using a lock-in system and the optimum phase matching temperature was set at 32 °C, a maximum SH output of 300 mW with the conversion efficiency of 75% was obtained.

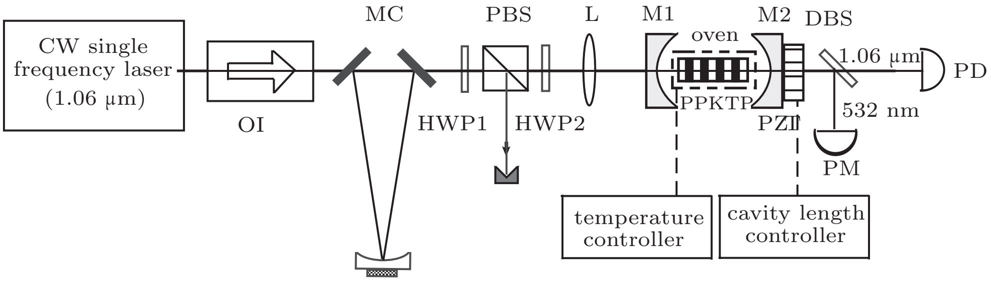

Fig. 1. Schematic diagram of the experimental setup. OI, optical isolator; MC, mode cleaner; PBS, polarizing beam splitter; HWP, half wave plate; M1, input coupler; M2, output coupler; PZT, piezoelectric transducer; DBS, dichroic beam splitter; PD, photodiodes; PM, power meter.

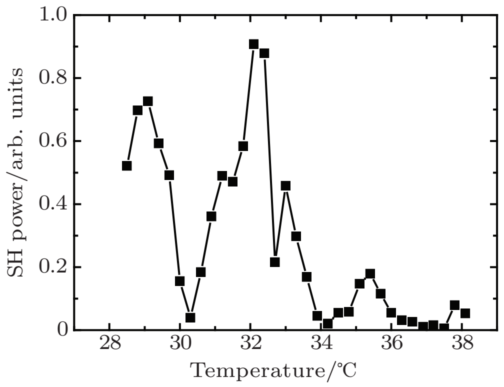

Fig. 2. Normalized SH power from the frequency doubler as a function of temperature of the PPKTP crystal.

To investigate the phase matching of the frequency doubler, the SH power was recorded as a function of the PPKTP temperature. Figure 2 shows the normalized phase matching curve for crystal temperature in a range between 28 °C and 39 °C. The curve in Fig. 2 is not well described by a sinc function. The additional peak at a temperature of about 29 °C is most likely to be due to the fact that difference in phase shift between fundamental and harmonic waves occurring at the high reflector leads to significant interference effects.[10] As described in Refs. [9] and [10], the cascaded second-order nonlinearity can be observed at the point of near-zero minimal SHG efficiency. In our experiment, the strongly asymmetric line shape of the fundamental mode was observed (the asymmetry curve is similar to that in Fig. 5 of Ref. [10]) at the point of minimal SH conversion (the PPKTP temperature was 34 °C) when the cavity was scanned through resonance linearly at a frequency of 150 Hz. This kind of strong asymmetry of the line shape demonstrated that the large nonlinear phase shift induced by the cascading second-order nonlinearity existed. It should be mentioned that when the cavity was scanned at a frequency of less than 100 Hz, a strong thermal effect due to the absorptions of fundamental and harmonic fields by the PPKTP crystal was also observed.

3. Observation of square-wave self-oscillations, the model and simulations

Usually, the transmitted fundamental intensity is stable at any cavity detuning and PPKTP temperature. However, when the PPKTP temperature was controlled at about 34 °C, the pump power incident to the frequency doubler was between 200 mW and 250 mW, and the cavity detuning was small (near the cavity resonance), a sustained square-wave self-oscillation of the transmitted fundamental intensity was observed. Figures 3(a)–3(c) show the typical self-oscillations at different cavity lengths with a pump power of 250 mW. The time scale of self-oscillations ($\sim 10^{-4}$ s) is a few orders of magnitude larger than cavity lifetime ($\sim 10^{-8}$ s). The duty cycle of the self-oscillations is dependent on the initial detuning of the cavity. When the cavity length was decreased slightly from the cold cavity resonance, namely the initial detuning of the cavity increased, the duty cycle of the self-oscillations was increased.

When the frequency doubler was at resonance, the self-oscillation vanished and the transmitted fundamental intensity was stable. Because we are mainly interested in studying dynamical effects, the cavity length was not stabilized by a feedback loop. However, by carefully designing the cavity and improving the frequency stability of the single-frequency pump laser and the thermal self-locking, the sustained self-oscillations could be maintained for several minutes at a fixed cavity length. In addition, the pump power of 200 mW was the critical intensity to obtain the regular and square-wave self-oscillations. When the pump power was below 200 mW, the self-oscillations had some irregular peaks.

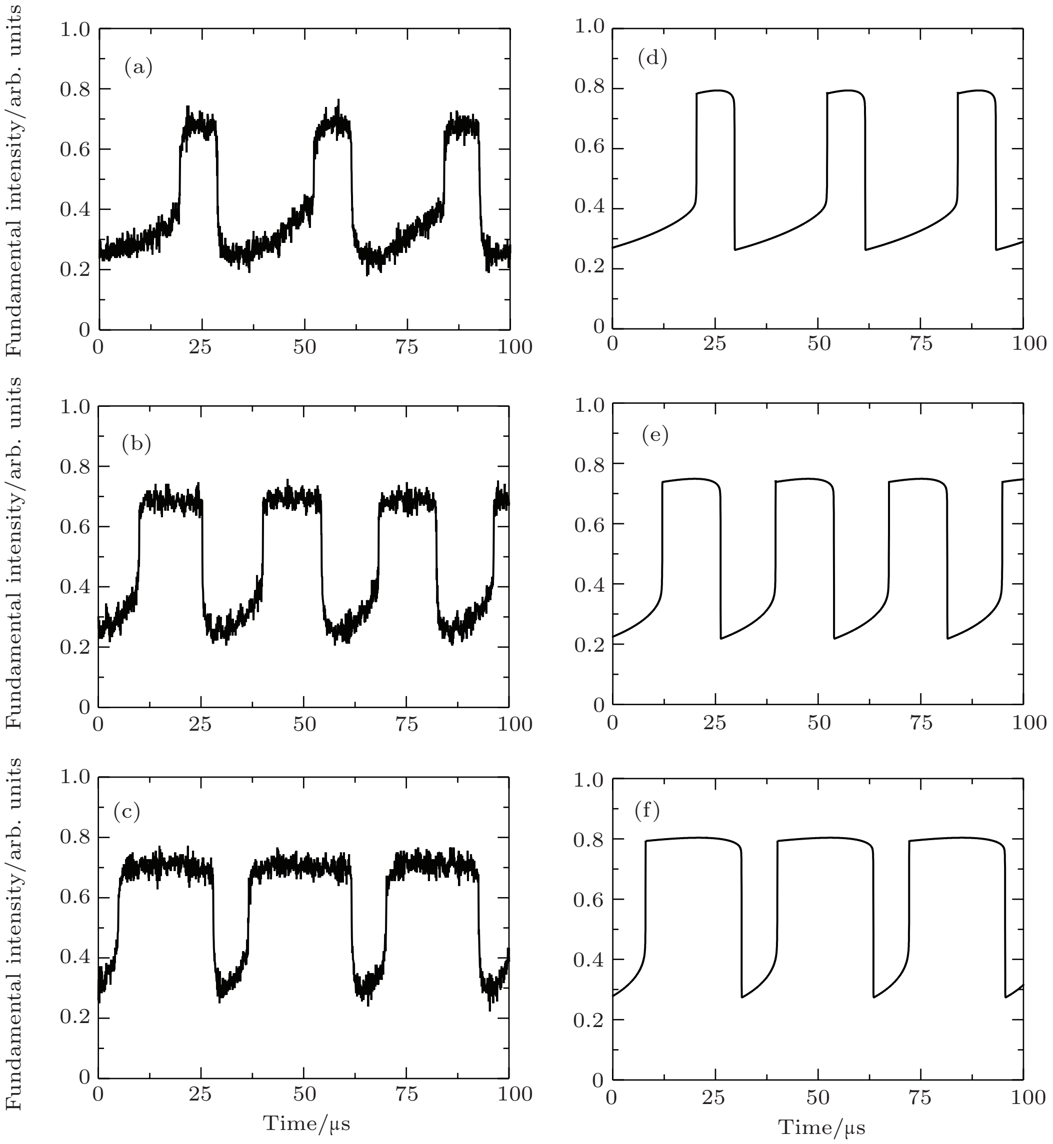

Fig. 3. Experimental results of square-wave self-oscillations of the transmitted fundamental intensity at different cavity lengths when the pump power is below the threshold of the SPO (panels (a)–(c)) and the theoretical simulation results (panels (d)–(f)), with the parameters used in the simulation being $\phi_0 = -0.035$ (d), -0.055 (e), and -0.080 (f).

The self-oscillations can be explained by the competition between two mechanisms with different response times and contributions opposite to the roundtrip phase shifts of the cavity. The competition model for the self-oscillations can be described by[11]

$$\frac{\mathrm{d}\phi_1(t)}{\mathrm{d}t} = \frac{-\phi_1(t) + \beta_1 I_{\mathrm{c}}^{\omega}(t)}{\tau_1}, \tag{1a}$$

$$\frac{\mathrm{d}\phi_2(t)}{\mathrm{d}t} = \frac{-\phi_2(t) + \beta_2 I_{\mathrm{c}}^{\omega}(t)}{\tau_2}, \tag{1b}$$

$$I_{\mathrm{c}}^{\omega}(t) = I_{\mathrm{in}} \frac{T_1}{(1 - r_1 r_2^{\mathrm{eff}})^2 + 4 r_1 r_2^{\mathrm{eff}} \sin^2\left(\dfrac{\phi_0 + \phi_1(t) + \phi_2(t)}{2}\right)}, \tag{1c}$$

where $\phi_1(t)$ and $\phi_2(t)$ denote the round trip phase shifts induced by cascading nonlinearity and thermal effect for fundamental, respectively; ϕ_0 is the initial detuning of the cavity from resonance; τ_1 and τ_2 are the response times, β_1 and β_2 are the constants governing the strengths of the two mechanisms, respectively; I_{in} and $I_{\text{c}}^{\omega}(t)$ are the incident fundamental intensity and the circulating fundamental intensity in the cavity respectively; T_1 and r_1 are the fundamental intensity transmission and amplitude reflectivity of the input coupler, respectively; r_2^{eff} is the effective amplitude reflectivity of the output coupler for fundamental mode with considering the nonlinear conversion and other linear losses. The transmitted fundamental intensity from the frequency doubler can be given by

$$I_{\text{t}}^{\omega}(t) = I_{\text{c}}^{\omega}(t)/T_2, \tag{2}$$

where T_2 is the intensity transmission of the output coupler for fundamental mode.

Table 1. Physical parameters of the PPKTP crystal.

Name	Symbol	Unit	Value
Length	L	mm	10
Poled period	Λ	μm	9
Nonlinear coefficient	d_{33}	pm/V	14.9
Absorption coefficient for fundamental mode	α_1	cm^{-1}	0.1%
Absorption coefficient for harmonic mode	α_2	cm^{-1}	2.5%
Thermo-optical coefficient	$\mathrm{d}n_z/\mathrm{d}T$	$^{\circ}\text{C}^{-1}$	1.44×10^{-5}
Thermal conductivity	K_{c}	W/(m·°C)	13

Listed in Table 1 are the physical parameters of the PPKTP crystal. In our experiment, the measured fineness of the frequency doubler was 120 at the point of minimal SH conversion. Using these parameters and the cavity parameters described in the experimental setup, and under the mean-field approximation, we could obtain the following variables: β_1 is -4.81×10^{-15} rad·cm^2/W, β_2 is 1.44×10^{-14} rad·cm^2/W, τ_1 is 0.62×10^{-8} s, τ_2 is 2×10^{-4} s, and r_2^{eff} is 0.9835.

Using the experimental parameters, the physical parameters of the PPKTP and the initial detuning of the cavity from resonance (ϕ_0) are set to be -0.035 (Fig. 3(d)), -0.055 (Fig. 3(e)), and -0.080 (Fig. 3(f)), respectively, the transmitted fundamental intensity from the frequency doubler can be theoretically simulated by Eqs. (1) and (2), and the results are shown in Figs. 3(d)–3(f). It can be seen that the calculated results are in good agreement with the experiment data.

4. Observation of staircase curve self-oscillations, the model and simulations

When pump power incident to the frequency doubler was increased and above the threshold of SPO,[15] the sustained staircase curve self-oscillations of the transmitted fundamental intensity could be observed. Figures 4(a)–4(d) show the self-oscillations at different cavity lengths with a pump power of 380 mW. When the cavity length is nearly that for the cold cavity resonance, the curve of self-oscillations is similar to the square-wave self-oscillations in Section 3 except an initial spiking as shown in Fig. 4(a). The initial spiking with a time scale of about 1 μs is due to a dynamical effect of delayed bifurcation.[16] When the cavity length was slightly decreased, a sustained staircase curve of self-oscillations could be observed as shown in Fig. 4(b). The duty cycle of the self-oscillations is dependent on the length of the cavity. As the cavity length was decreased, the width of the middle step was expanded. When the cavity length was decreased to a certain point, the frequency doubler was self-locked and the transmitted fundamental intensity with the amplitude of middle value was stable as shown in Fig. 4(c). When the cavity length was decreased further, the self-oscillations appeared again. In this case, the self-oscillation amplitude curve was superposed on a mean value and the duty cycle was also dependent on the initial detuning of the cavity as shown in Fig. 4(d).

This kind of self-oscillation can be explained by the competition between the phase shift induced by cascading nonlinearity and thermal effect, and the influence of fundamental nonlinear phase shift by the generation of SPO. The propagation equations for SPO are given by[17]

$$\frac{\mathrm{d}A_1(z)}{\mathrm{d}z} = -\mathrm{i}g_0 u^*(\Delta k, z) A_1^*(z) A_2(z), \tag{3a}$$

$$\begin{aligned}\frac{\mathrm{d}A_2(z)}{\mathrm{d}z} = &-\mathrm{i}\frac{g_0}{2} u(\Delta k, z) A_1(z)^2 \\ &- \mathrm{i}g u(\Delta K, z) A_i(z) A_{\text{s}}(z),\end{aligned} \tag{3b}$$

$$\frac{\mathrm{d}A_{\text{s/i}}(z)}{\mathrm{d}z} = -\mathrm{i}g u^*(\Delta K, z) A_{\text{s/i}}^*(z) A_2(z), \tag{3c}$$

where A_j ($j = 1$, 2, s, i) denote the complex amplitudes of fundamental, harmonic, signal, and idler, respectively; g and g_0 are the gain coefficients each with a value of 2.65×10^3 when a near-degenerate SPO operation is considered; $u(\Delta k, z)$ can be reduced to $\exp(\mathrm{i}\Delta k z)$ when the waves are weakly focused (near-field case); Δk and ΔK are the wave-vector mismatches for the SHG and the near-degenerate SPO, respectively. At the point of minimal SH conversion, $\Delta k L$ is equal to 2π and

ΔKL is equal to zero (L is the length of PPKTP crystal). Using Eq. (29) in Ref. [17] and our experimental parameters, the threshold of SPO is calculated to be 260 mW. Using a Fabry–Perot spectrum analyzer to monitor the transmitted fundamental field from the frequency doubler, the existence of down-converted parametric fields was observed with a threshold of about 270 mW.

Using the experimental parameters and the physical parameters of the PPKTP and the initial detuning of the cavity from resonance (ϕ_0) set to be -0.030 (Fig. 4(e)), -0.070 (Fig. 4(f)), -0.095 (Fig. 4(g)), and -0.130 (Fig. 4(h)), the transmitted fundamental intensity from the frequency doubler can be theoretically simulated by Eqs. (1)–(3) as shown in Figs. 4(e)–4(h). It can be seen that the simulation results are in good agreement with the experiment data.

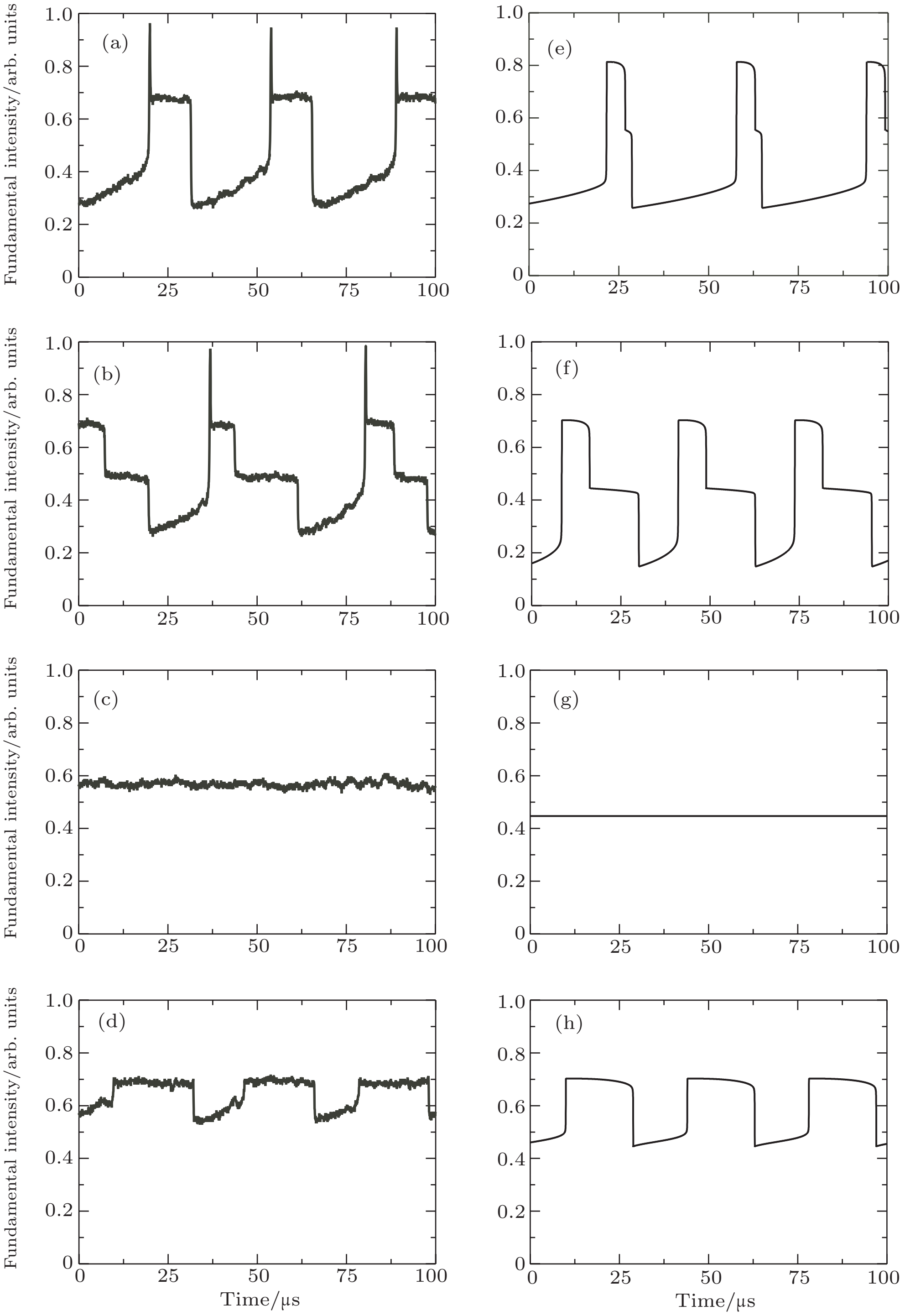

Fig. 4. Experimental results of staircase curve self-oscillations of the transmitted fundamental intensity at different cavity lengths when the pump power is above the threshold of the SPO (panels (a)–(d)) and the theoretical simulation results (panels (e)–(h)), with parameters used in the simulation being $\phi_0 = -0.030$ (e), -0.070 (f), -0.095 (g), and -0.130 (h).

5. Conclusions

In this paper, we observed self-oscillations from a PP-KTP frequency doubler which is singly resonant for fundamental mode at the point of minimal SH conversion. The sustained square-wave self-oscillations and staircase curve of self-oscillations can be obtained when the incident pump powers are below and above the threshold of SPO, respectively. The self-oscillations can be explained by the competition between the phase shift induced by cascading nonlinearity and thermal effect, and the influence of fundamental nonlinear phase shift by the generation of SPO. The simulation results are in good agreement with the experiment data. The observed self-oscillations enhance our understanding of the dynamics of nonlinear phase shift and thermal induced phase shift and their interactions. The cascaded second-order nonlinearity can be applied to all optical switching, light pulse regeneration and reshaping, quantum optics, and so on.

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