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Abstract. A critical physical phenomenon of polarization instability was observed in periodically poled lithium niobate, which reveals that tiny changes in the exterior conditions will have a remarkable effect on the polarization state of the output light. The instability shown here has a new physical mechanism from those in the weakly dispersive fiber, and such an in-chip chaos system is likely to promote an integrated chaos device behaving as biosensor, switch, and filter with high sensitivity or resolution. [DOI: 10.1117/1.OE.55.1.017105]

Keywords: modulational instability; beat length; periodically poled lithium niobate.

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1 Introduction

In weakly dispersive fiber, when an intensive light is propagating, due to the third-order nonlinear effects, the discrepancy between the refractive index of the ordinary wave and the extraordinary wave will gradually decline and eventually vanish at a critical distance, leading to a beat length so sensitive to the light intensity and the incident polarization state that tiny changes in it will cause tremendous changes to the output state.[1–8] It was believed that such modulational instability of polarization could not exist in the traditional bulk crystal because the birefringence here is too large to be completely counteracted within the ablation threshold. Although incorrect in the traditional bulk crystal, will this conclusion still hold in crystals with microstructures?

In past decades, ferroelectric domain structure has become a hot topic and inspired plans to create many crucial applications owing to so-called quasiphase match (QPM) technology.[9–14] Significantly less research has paid attention to whether instability of polarization can occur in such a structure. However, in this paper, we demonstrate that in periodically poled lithium niobate (PPLN), a critical physical phenomenon strongly coherent to polarization instability surprisingly exists, where the beat length is so sensitive to the external electric field that tiny deviations of the field intensity about zero will cause the beat length to experience tremendous changes; more interestingly, the smaller the electric field intensity, the larger the beat length.

In contrast with the modulational instability of polarization in weakly dispersive fibers, the phenomenon presented in this paper is, interestingly, a step change rather than a fast change, and it relies on second-order nonlinear effects instead of third-order ones. The results have opened a new perspective toward the ferroelectric domain structure in which a PPLN chip is actually a chaos system whereby the influence of the exterior perturbation can never be ignored, especially when it is extremely small. We believe this modulational instability of the polarization phenomenon will find a wide range of interest.

2 Theory Analysis

When a transverse external electric field is applied along the PPLN, based on the electric-optical effect, the optical axis of each domain is alternately aligned at the angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light.[15] The relative azimuth angle between the dielectric axes of two adjacent domains is small so that the periodic alternation of the azimuth can be considered a periodic small perturbation. In this case, the coupled-wave equations of the ordinary and extraordinary waves with a periodic small perturbation are

$$\begin{cases} dA_1/dz = -i\kappa A_2 \exp(i\Delta\beta' z), \\ dA_2/dz = -i\kappa^* A_1 \exp(-i\Delta\beta' z), \end{cases} \tag{1}$$

with

$$\Delta\beta' = \Delta\beta - G_m,$$

$$G_m = 2\pi m/\Lambda,$$

and

$$\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi}\,(m = 1, 3, 5\dots),$$

where G_m is the m'th reciprocal vector corresponding to the periodicity of poling, Λ is the period of the PPLN, γ_{51} is the electro-optical coefficient, and E_y is the electric field intensity. n_o and n_e are the refractive index of the ordinary wave and the extraordinary wave, respectively. The solution of coupled mode [Eq. (1)] is

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$$\begin{cases} A_1(z) = \exp[i(\Delta\beta'/2)z]\{[\cos(sz) - i\Delta\beta'/(2\ s) \\ \qquad \times \sin(sz)]A_1(0) - i(\kappa/s)\ \sin(sz)A_2(0)\}, \\ A_2(z) = \exp[-i(\Delta\beta'/2)z]\{(-i\kappa^*/s)\ \sin(sz)A_1(0) \\ \qquad + [\cos(sz) + i\Delta\beta'(/2s)\ \sin(sz)]A_2(0)\}, \end{cases} \tag{2}$$

with $s^2 = (\Delta\beta'/2)^2 + \kappa\kappa^*$. From the solution, the output light will restore its polarization state when $sz = 2n\pi$, $(n = 1, 2, 3\ldots)$, and the beat length is given by

$$L_0 = 2\pi/s = 2\pi/\sqrt{(\Delta\beta - G_m)^2/4 + \kappa\kappa^*}.$$

In PPLN, the beat length under the zero electric field and nonzero electric field is given by

$$\begin{cases} L_0 = 2\pi/\Delta\beta, & \kappa = 0, \\ L_0 = 2\pi/\sqrt{(\Delta\beta - G_m)^2/4 + \kappa\kappa^*}, & \kappa \neq 0. \end{cases} \tag{3}$$

Equation (3) indicates that the external electric field has introduced a reciprocal vector in the expression of the beat length, which is able to completely counteract the mismatch of the phase $\Delta\beta$ between the ordinary wave and the extraordinary wave.

The comparison of $\Delta\beta$ and κ is shown in Fig. 1(a),where the period of the PPLN is 21 μm, wavelength is 1540.3 nm, temperature is 18.48 ℃, and the electric field intensity is from 0.01 to 1 V/μm; apparently, κ is much smaller than $\Delta\beta$. For wavelengths satisfying the QPM condition, which is $\Delta\beta - G_m = 0$, the beat length is simplified to $L_0 = 2\pi/|\kappa|$. Then, if κ is in the vicinity of 0, a tiny change to κ, $\Delta\beta$, or G_m will lead to a tremendous change of the beat length. In Fig. 1(b), if κ shifts from zero to nonzero, then the beat length will experience a sharp change; and the smaller the electric field intensity, the larger the beat length. However, κ cannot be exactly 0 but infinitely close to 0, because when $\kappa = 0$, the reciprocal vector will suddenly vanish, leading the beat length to experience a marked change from infinitely large to a finite value. The detailed chain reaction of the modulational instability of polarization is shown in Figs. 1(c) and 1(d). Here, the domain angle θ caused by the external electric field will lead to a large change in the polarization state. Figure 1(c) is the condition with no electric field, where the polarization state of the light periodically circles along a closed circular path on the Poincare sphere with the beat length equal to the period of the PPLN. Figure 1(d) is the condition with an electric field, where the evolution of the optical polarization is like a spiral, so the state of the light will deviate a little from the incident state every period of the PPLN until the difference reaches the max, after which the light will begin to restore. In this case, the light does experience a much longer beat distance than the former condition. From Fig. 1(d), the pitch of A_0' and A_1 is changed by the domain angle θ; the smaller the domain angle θ, the smaller the pitch, so the longer the distance the light needs to complete in such a chain process to restore to the initial state.

3 Experimental Results and Discussion

The schematic of the experimental setup is shown in Fig. 2. The thickness of the PPLN is 0.5 mm and the width is 1 cm. We then fabricate a Z-cut PPLN chip with 3000 domains as well as with three periods of 20, 21, and 22 μm to verify the modulational instability of polarization of light. For the sample with a period of 21 μm at room temperature, the QPM wavelength $[\lambda_0 = \Lambda(n_e - n_o)]$ is calculated at 1540.3 nm using the Semiller equation. [16] Then, a tunable laser is employed to generate such a wavelength. Figure 1(c) suggests if there is no electric field applied to the sample, the

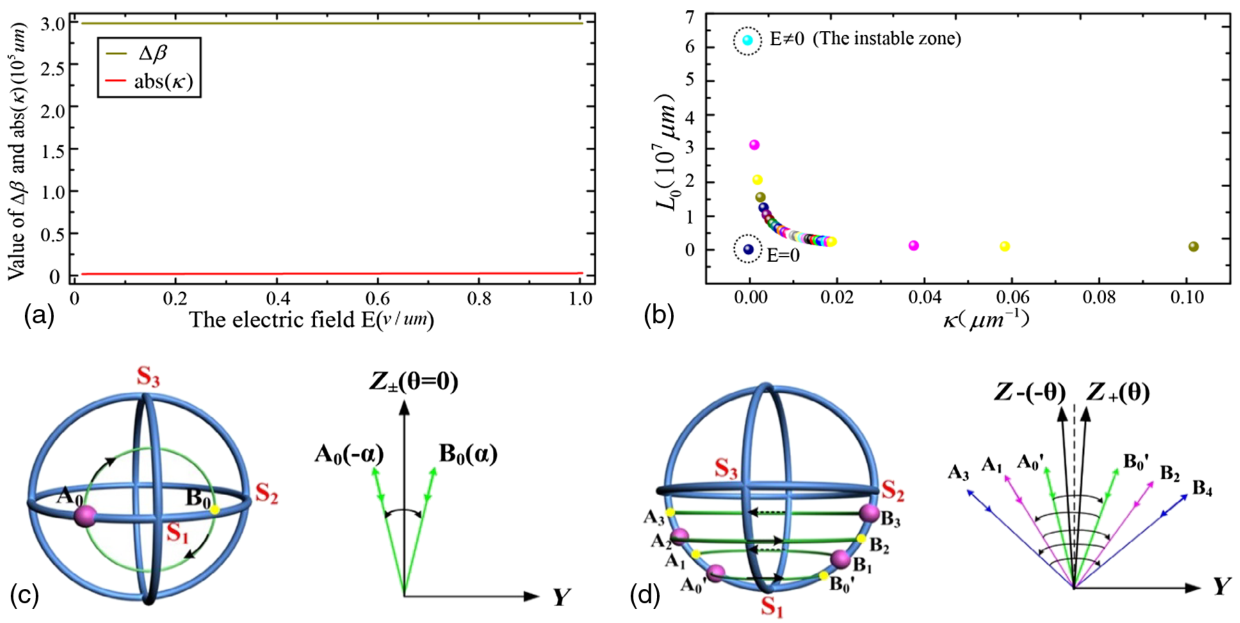

Fig. 1 Theoretical results of the polarization-state instability. (a) The comparison of $\Delta\beta$ and κ is shown; (b) the beat length as a function of the coupling coefficient κ, which is controlled by the applied electric field for wavelength fulfilling the QPM condition, is shown; (c) and (d) the detailed chain reaction of the butterfly effect is shown, where $-\alpha$ is the polarization angle of a linearly polarized light satisfying the QPM condition and θ is the domain angle caused by the electric field.

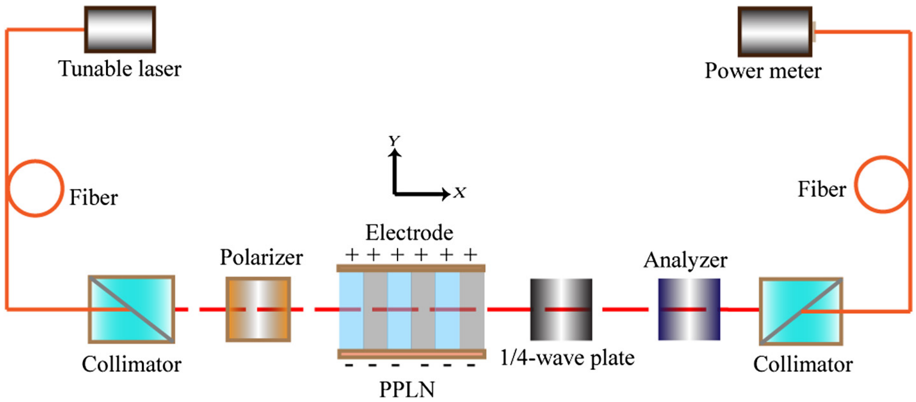

Fig. 2 Schematic of the experimental setup for investigating the polarization state of light. The PPLN crystal is Z cut with the period of 21 μm. A uniform electric field is applied along the Y-axis of PPLN.

polarization state of the QPM wavelength will restore to the incident state after passing the integral periods of the PPLN. However, if an external electric field is presented, the beat length will be quickly increased due to the chain reaction, and the output state may differ from the incident state. However, the experimental results shown in Fig. 3(a) demonstrate that with no electric field, the 1540.3 nm light linearly polarized along both the Z-axis and Y-axis has rotated slightly by the Z-axis rather than remaining unchanged, which seems in contradiction to the theoretical analysis. We also measured the output state, which is changed by the external electric field, as shown in Fig. 3(b).

Previous researchers have revealed that in such a periodically poled structure, an initial angle of the domain axis surprisingly exists, which may be caused by the strain-optic effect [17] produced in the process of polarization or by the photovoltaic effect [18] engendered by the input light. Due to the initial domain angle, the chain reaction happened and resulted in a discrepancy between the experimental results and the calculation results. When an external electric field is applied along the Y-axis, it was found that the positive electric field and the negative electric field have different effects on the output state. With the negative electric field, the output state gradually moves to the incident

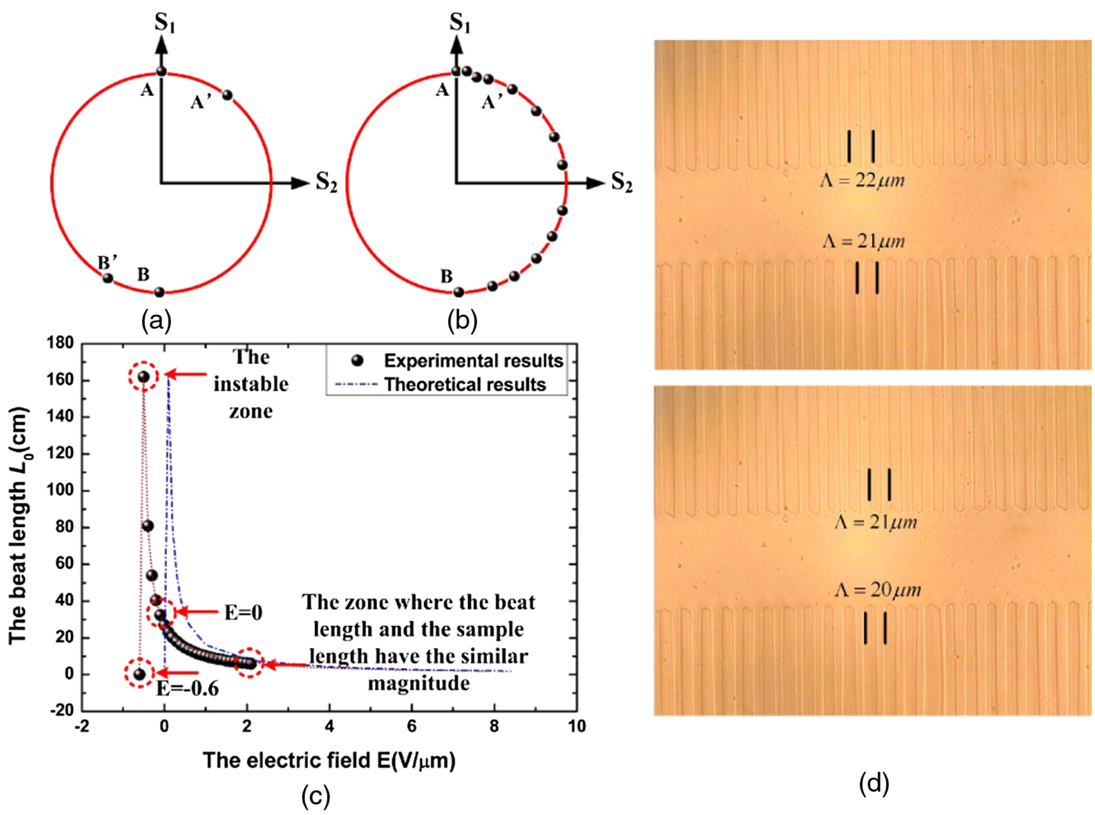

Fig. 3 Experimental results of the modulational instability of polarization. (a) The condition with no electric field is shown, where A, B is the input state and A', B' is the output state. (b) The condition with different electric fields and (c) the beat length at each electric field are shown. (d) The microstructure of the PPLN sample with three periods of 20, 21, and 22 μm is presented.

state, which means that the field has minimized the initial domain angle and the beat length has been quickly increased. When the beat length is large enough that the sample is much shorter than the beat length, the output light will rarely change except in the vicinity of the incident light. Instead, the positive field will enlarge the domain angle and shorten the beat length. Once it is shortened at the sample level, the output state will become sensitive to the electric field and will show marked change with it. Deduced from the analysis on the experimental results, the beat length at each electric field is shown in Fig. 3(c). At the field of $-0.6\ \mathrm{V}/\mu\mathrm{m}$, the domain angle has vanished and the beat length equals the period of the PPLN sample. At the field of $2.1\ \mathrm{V}/\mu\mathrm{m}$, the output state has rotated $\pi/2$ by the Z-axis (B state) and the beat length is twice that of the sample. And in the zone where the beat length and the sample length have similar magnitudes, the output state is sensitive to the electric field and may function as a new electro-optical device, which has an advantage of extremely high sensitivity. The microstructure of the PPLN sample is shown in Fig. 3(d).

In the theoretical analysis, when $\kappa \neq 0$, the beat length is given by $L_0 = 2\pi/\sqrt{(\Delta\beta - G_m)^2/4 + \kappa\kappa^*}$. If κ is a fixed small value, the beat length is also sensitive to G_m and $\Delta\beta$. Then, consider a given wavelength of 1540.3 nm incident into the PPLN, and the beat length can be rewritten to $L_0 = 2\pi/\sqrt{\pi^2(1/\Lambda_0 - 1/\Lambda)^2 + \kappa\kappa^*}$, where Λ_0 is

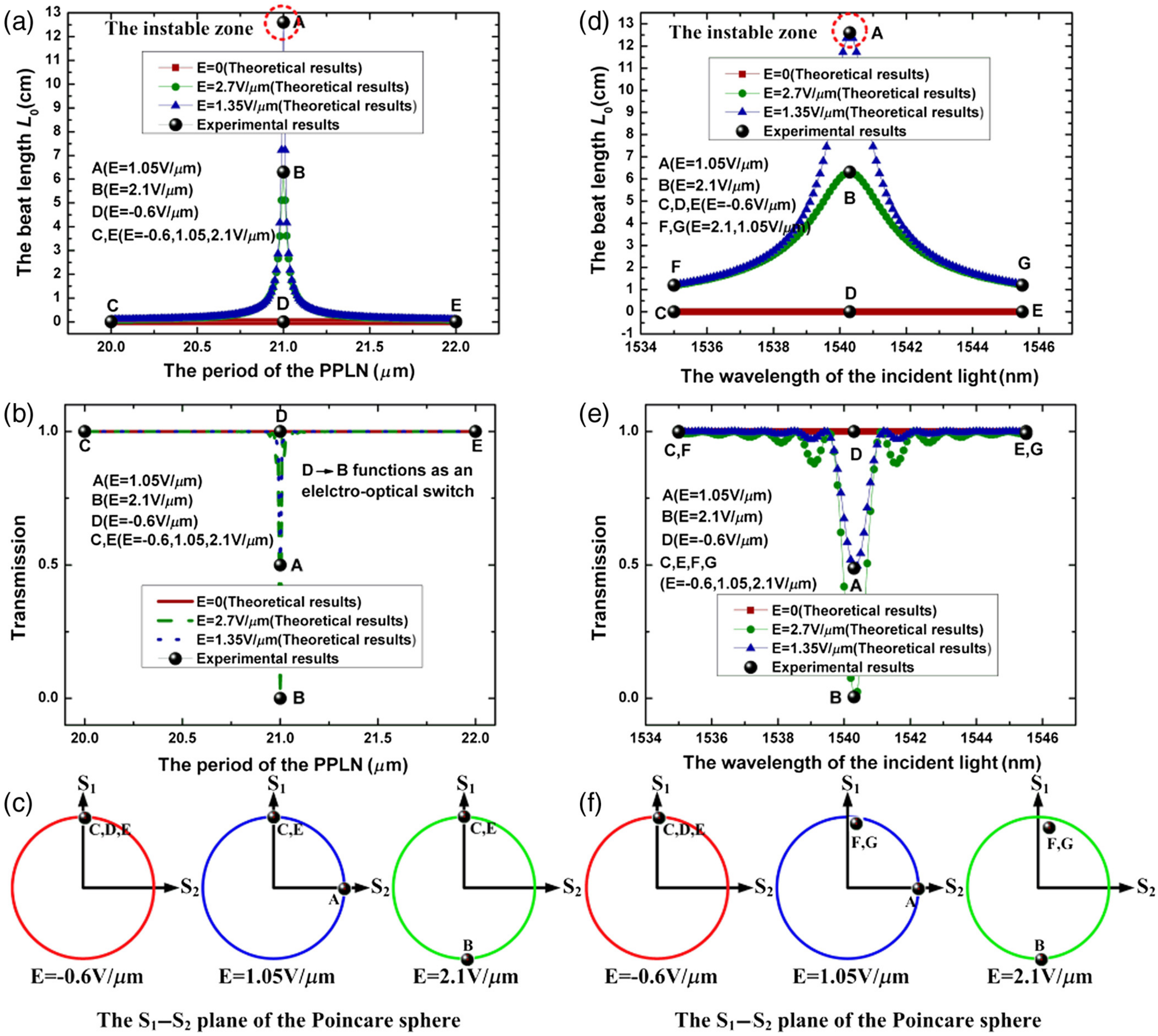

Fig. 4 Experimental results of the modulational instability of polarization of G_m and λ. (a)–(c) show the instability of G_m, and (d)–(f) present the instability of λ. In (a)–(c), the wavelength is fixed at 1540.3 nm, and in (d)–(f), the period of the PPLN is fixed at 21 μm. With no electric field, the beat length is a small value in both cases. Then, a tiny field will cause remarkable change of the beat length around the period of 21 μm in (a) as well as around 1540.3 nm in (d); (b) and (e) present the transmission of the output light after passing a parallel analyzer; (c) and (f) present the polarization state of the output light on the $S_1 - S_2$ plane of the Poincare sphere.

21 μm and Λ is the period of an arbitrary PPLN sample. However, if considering a given sample with $\Lambda = 21\ \mu$m, the beat length can be rewritten to $L_0 = 2\pi/\sqrt{(\lambda_0\pi/\Lambda_0)^2(1/\lambda_0 - 1/\lambda)^2 + \kappa\kappa^*}$, where λ_0 is the QPM wavelength of 1540.3 nm and λ is an arbitrary wavelength. Figure 4 presents the experimental results of both cases, with Figs. 4(a)–4(c) showing the instability of G_m and Figs. 4(d)–4(f) presenting the instability of $\Delta\beta$, which is consistent with the theoretical analysis. For the former case, a tiny change of the period of the PPLN away from 21 μm will cause a drag change of the beat length as well as the transmission of the light after passing a parallel analyzer if the length of the crystal is more or less the same as the beat length. Here, the unstable zone for the 1540.3 nm light is in the vicinity of the period of 21 μm. For the latter case, a little change in the wavelength of the incident light away from 1540.3 nm will lead to the same effect as the former case, and the unstable zone for the 21 μm sample is around the 1540.3 nm wavelength. Although in the unstable zone, the smaller the electric field, the larger the beat length, the transmission and the polarization state of the output light has an optimum electric field under which the beat length and the sample length have the same magnitude and both the transmission and the polarization state will have notable sensitivity with G_m and λ. All the experimental results have agreed well with the theoretical results. Besides, both the cases have revealed that if the length of the PPLN is infinitely large, then the output state can be notably sensitive to the external electric field, the wavelength of the input light, and the period of the PPLN.

4 Conclusion

In summary, we have proposed a critical phenomenon of modulational instability of polarization of light with the essence of the chaos effect in PPLNs, which reveals that the beat length is very sensitive to the electric field and that tiny changes to the field will have a large effect on the output state. Moreover, the smaller the electric field, the larger the impact on the light. The perturbation of the electric field here leads to a tremendous change in the polarization state of the wave in the PPLN. In particular, this modulational instability of polarization has a different physical mechanism from the existent polarization instability, which employs a reciprocal vector to counteract the birefringence instead of using third-order nonlinear effects. Because the reciprocal vector appears suddenly with the external electric field, the instability is interestingly a step change rather than a fast change and will be likely to promote optical devices with infinitely high sensitivity. We believe such polarization-state instability in a PPLN chip will open a new perspective toward QPM technology and find a wide range of interest.

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