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Evolution of the optical polarization in a periodically poled superlattice with an external electric field

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The polarization behavior of the electromagnetic waves under external electric field in the periodically poled optical superlattice is experimentally observed, which reveals that for the QPM wavelengths [fulfilling the quasi-phase-matched (QPM) condition] the evolution of the polarization exhibits generated paths along the Poincare sphere, but for the NQPM wavelength (not fulfilling the QPM condition) it will split into discrete paths. These phenomena are likely to promote a novel method for a precise polarization control.

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In the past decades, the ferroelectric domain structure has become a noted topic and inspired plans to create many crucial applications owing to the so-called quasi-phase-matched (QPM) technology [1–7]. Researches on such a structure have so far focused predominately on wavelengths, which satisfy the QPM condition, and significantly less work has paid attention to other wavelengths. It would be interesting to discover novel phenomenon beyond that condition, which will be likely to promote novel applications and original ideas in such a domain inverted structure. Meanwhile, the polarization state of the light, which reflects the vector nature of the electromagnetic field and introduces topological features with important implications regarding discrimination and robustness of certain electromagnetic interactions, is particularly striking when nonreciprocity comes into play and can have some far reaching conceptual repercussions in applications, which is—for instance—the case when unidirectional control or shielding of optical signal transfer is an issue or, in connection with the storage and transfer of coherence, quantum optical or spin coherence in particular [8–11].

Although several studies have been reported on the polarization the evolution of polarization states of light in ferroelectric domain structures and many remarkable effects have been predicted and studied [12,13], the investigation of the polarization evolution with novel properties in ferroelectric domain structures is still striking. In this paper, we filled the vacancy of the investigation of the wavelengths disagreeing with the QPM condition (we call it the NQPM wavelengths) in periodically poled lithium niobate (PPLN) and proposed the original idea about the discrete paths in polarization evolution, which may create a new perspective toward the QPM technology. We experimentally discovered that for the NQPM wavelengths the polarization follows successive continuous but discrete paths on the Poincare sphere with increasing electric field. However, for the QPM wavelengths, the discrete paths suddenly degenerate and are parallel to the equator plane. Interestingly enough, we also found that the QPM wavelength is actually an instable point, where a tiny change in the wavelength will cause a notable change in the output state. In addition, the paths of both kinds also behave disparately with different incident states of polarization.

The idea is achieved on the basis of electro-optic effect of PPLN, first theoretically proposed by Lu *et al.* [14] and afterward experimentally proven by Chen *et al.* [15]. We have demonstrated a linear polarization-state generator for the QPM wavelengths in such a structure previously [16]. To get an insight into the behavior of the NQPM wavelengths, a polarization coupled-mode theory is established to track the polarization state of light propagation along PPLN. At the output of PPLN, the solutions of the coupled-wave equations of the ordinary and extraordinary waves are given by [17]

$$A_1(L) = \exp[i(\Delta\beta/2)L]\{[\cos(sL) - i\Delta\beta/(2s)\sin(sL)]A_1(0) - i(\kappa/s)\sin(sL)A_2(0)\},$$

$$A_2(L) = \exp[-i(\Delta\beta/2)L]\{(-i\kappa^*/s)\sin(sL)A_1(0) + [\cos(sL) + i\Delta\beta(/2s)\sin(sL)]A_2(0)\}, \qquad (1)$$

with $\Delta\beta=(k_2-k_1)-G_m$, $G_m=2\pi m/\Lambda$, $\kappa=-(\omega/2c)\times(n_o^2n_e^2\gamma_{51}E_y/\sqrt{n_on_e})[i(1-\cos m\pi)/m\pi]$ $(m=1,3,5,\ldots)$, and $s^2=\kappa\kappa^*+(\Delta\beta/2)^2$, where A_1 and A_2 are the normalized amplitudes of the ordinary and extraordinary waves, respectively; k_1 and k_2 are the corresponding wave vectors; G_m is the mth reciprocal vector corresponding to the periodicity of poling; L is the length of PPLN; Λ is the period of PPLN; n_o and n_e are the refractive indices of ordinary and extraordinary waves, respectively; γ_{51} is the electro-optical coefficient; and E_y is the electric field intensity. It is easily understood that the output light will restore its polarization state to the incident state when $sL=2n\pi$ $(n=1,2,3\ldots)$,

$$A_1(L) = \cos(|\kappa|L)A_1(0) - \sin(|\kappa|L)A_2(0),$$

$$A_2(L) = \cos(|\kappa|L)A_2(0) + \sin(|\kappa|L)A_1(0). \qquad (2)$$

Specifically, for the QPM wavelength $(\Delta\beta=0)$, solutions (1) can be simplified to Eqs. (2), which reveals that the output polarization state will periodically changes with $|\kappa|L$, resulting in the degenerated paths of evolution along the Poincare sphere (shown in Fig. 1). But for the NQPM wavelength $(\Delta\beta\neq0)$, the evolution of the polarization state starts and ends at the same polarization state (the initial polarization

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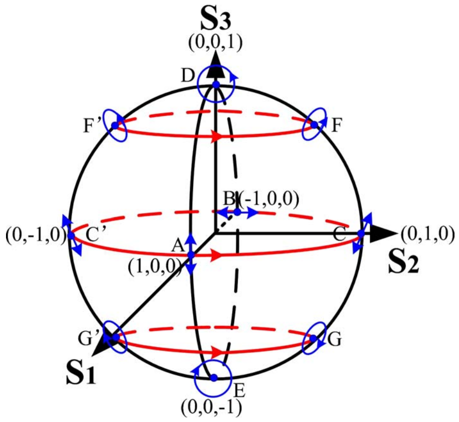

FIG. 1. (Color online) Theoretical results of the degenerated paths of the QPM wavelength; for incident light linearly polarized such as A–C, the polarization of the output light evolves along the equator; for light circularly polarized (D and E), the output states remain unchanged and situated on the north and south poles, respectively.

state) but experiences different paths along the Poincare sphere, because besides the reliant parts of "sin(sL)" and "cos(sL)," which play a vital role on the periodic evolution, the paths of evolution are also dependent on the coupling coefficient κ, which is increasing with the electric field. Thereby, when the evolution is getting across the initial point each time and about to enter a new round of period, the new coupling coefficient κ will provoke the evolution to bypass the pretrack into a different path and eventually give birth to the interesting phenomena of split paths along the Poincare sphere (shown in Fig. 2).

In above discussions, we have proposed the concept of the discrete evolution paths for the NQPM wavelength according to the coupled-mode theory. To make the results more convincing, a different theory, the Jones matrix method, is thereafter employed to track the evolution of the polarization state on the Poincare sphere for both the QPM and NQPM wavelengths [18,19]. Distinctive incident polarization states linearly polarized along Z (A) and Y (B) axes, rotated 45° by the Z axis (C), and circularly polarized (D and E) are especially investigated, which show attractive properties in polarization-state control.

Figure 1 presents the numerical results using the Jones method for the QPM wavelengths, which reveals that the evolution of the polarization states periodically circles along a degenerated path with the external electric field, showing agreement with the analysis based on the coupled-mode theory. For the input light linearly polarized (A–C), the path is always right in the equator, which means that each linear polarization state on the path composes a group, in which the element can be transformed to any one included in the same group by modulating the external electric field.

Besides the group of linear states of polarization, distinctive other groups can also be discovered on the Poincare sphere. There into, D and E, the left- and right-hand circular states of polarization are two groups with only one element, respectively, which means that the path on the Poincare sphere is just a point, and F (or G) is an arbitrary elliptical polarization state whose path is parallel to the equator plane. For the linear polarization-state group, it is capable of designing devices behaving as the linear polarization-state generator [16] and, for other groups, it is also interesting to achieve orthogonal elliptical states of polarization such as states F and F′, which can be used in the satellite communication for doubling the capacity of the services [20].

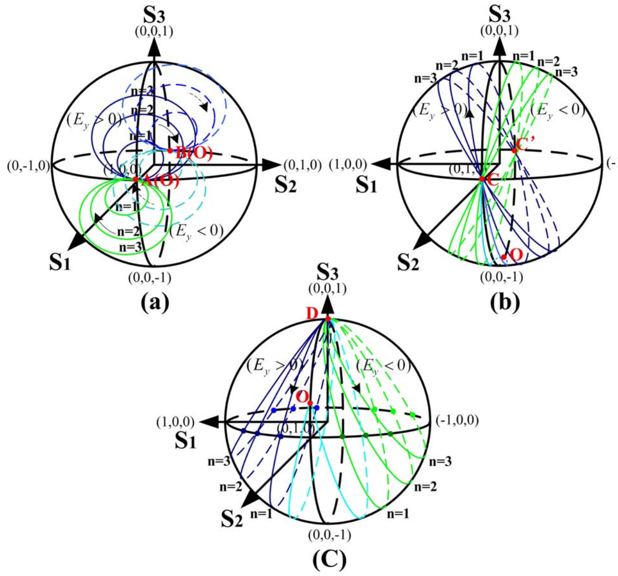

FIG. 2. (Color online) Theoretical results of the discrete paths of the NQPM wavelength; (a) the discrete paths of the output light with the incident light linearly polarized along the Z axis (solid curve) and linearly polarized along the Y axis (dash curve); (b) the discrete paths of the output light with the incident light linearly polarized rotated 45° by the Z axis; (c) the discrete paths of the output light with the incident light right-handedly circularly polarized. O is the initial state of polarization of the output light when no electric field is applied on the PPLN. In (b) and (c), due to the spontaneous birefringence, the initial output state is consequently different from the input state, respectively.

It is interesting to note that, in an input light with a specific polarization state of one group, if the incident state undergoes mutation but still belongs to the same group, the polarization state of the output light still can be pulled back with the external electric field. However, if the mutation makes the incident state jump into another group, it will never be restored but circle along another path forever. These different groups with different paths can be compared to the so-called energy levels along the Poincare sphere and the behavior of the path shift can be considered as the energy transition by analogy.

Then we move to investigating the NQPM wavelengths. Figure 2 reveals that the polarization evolution of such wavelengths does take on the discrete paths along the Poincare sphere and each path is corresponding to a specific quantum number. Consider an incident light with state A, when no electric field is applied, the output state is situated at point A [Fig. 2(a)]. Then with the increment of the electric field, the output state begins to circle along the inner path ($n=1$) and when passing by point A a second time the evolution alters the way and jumps into another path ($n=2$) and the rest may

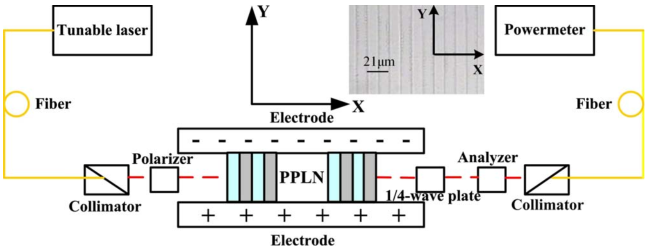

FIG. 3. (Color online) Experimental setup for investigating the polarization behavior of light; the PPLN crystal, used for managing the polarization, is *Z* cut and consists of 2858 domains with the period of 21 (μm). The input light with an arbitrary state of polarization propagates along the *X* axis. A uniform electric field is applied along the *Y* axis of the PPLN.

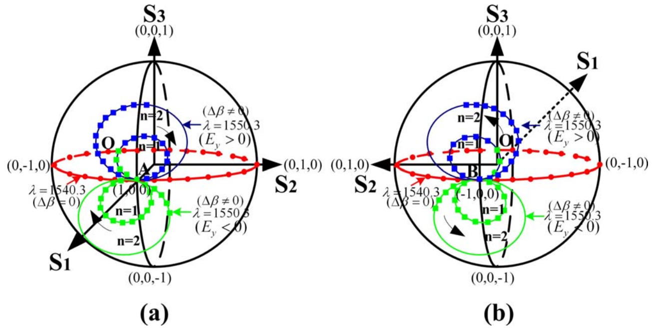

FIG. 4. (Color online) Experimental results of the polarization-state evolution with the external electric field for both the QPM and NQPM wavelengths; (a) the incident state of polarization is linearly polarized along the *Z* axis represented by point A; (b) the incident state of polarization is linearly polarized along the *Y* axis represented by point B. The curve with circular symbol denotes the experimental results for the QPM wavelength (1540.3 nm), while the curve with square symbol denotes the experimental results for the NQPM wavelength (1550.3 nm). For 1540.3 nm wavelength the path of polarization-state evolution is degenerated on the equator, while for 1550.3 nm wavelength the path abruptly splits into discrete paths.

be deduced by analogy. The phenomena suggest that by modulating the electric field and altering the incident states the Poincare sphere can be basically covered, which may play a vital role in the test of the polarization-dependent loss [21].

Uniquely, we discover that, when the incident state is the C state, the output state can be shifted between dual linear states of polarization [Fig. 2(b)], which is attractive when designing devices that function as the broadband electro-optical switch or laser-*Q* switch [22]. Besides, for incident light circularly polarized [Fig. 2(c)], the state of the output light periodically shifts between circularly and linearly polarized, which can be used for precise quantum coding [23].

To make conclusions more convincing, we also verified them with experiments. Figure 3 is the experiment setup for investigating the evolution of the polarization, where the temperature is 20 °C and the applied electric field is modulating from −0.3 to 0.3 V/μm. By the use of the $\lambda/4$ plate and the analyzer the polarization state of the output light can be determined. Experimental measurements for a given wavelength are shown in the Poincare sphere in Fig. 4. The dissimilarity between Figs. 4(a) and 4(b) is the different incident states of polarization; Fig. 4(a) is for light linearly polarized along the *Z* axis (state A) and Fig. 4(b) is for light linearly polarized along the *Z* axis (state B).

Figure 4 shows that, for the QPM wavelength, the degenerated path is circling along the equator plane for both incident states, but for the NQPM wavelength the discrete paths are exhibiting with different styles. In light of this, the evolution of the polarization for the NQPM wavelength is the one-directional evolution or the beamed evolution, which means that if one incident state can be transformed to another, the latter as the incident state, however, cannot be transformed to the former because the evolution does not simply drive back along the same path but anew takes another path, which is improbable to pass by the former state.

By changing the sign of the electric field from *Y* to −*Y* axis, the path correspondingly shifts from the upper sphere (left-handed spin) to the lower sphere (right-handed spin) by virtue of the change of sign of κ, which is coherent with the state of the output light. The mere deviation between the experiment and numerical results is the different starting points (point O) along the Poincare sphere, which results from the inner electric field existed in such a periodically poled ferroelectric domain structure that may be caused by the strain-optic effect [24] produced in the process of polarization or the photovoltaic effect [25] engendered by the input light.

The experimental results in Fig. 5 show that in the vicinity of the QPM wavelength the output state is too sensitive to the wavelength that a tiny change in the wavelength will cause a remarkable change in the output state; and the smaller the deviation, the larger the effect on the output light, which is similar to the phenomenon of polarization instability [26–29]. This is because the beat length is given by $L_0 = 2\pi/\sqrt{(\Delta\beta/2)^2+\kappa\kappa^*}$. For the QPM wavelength we have

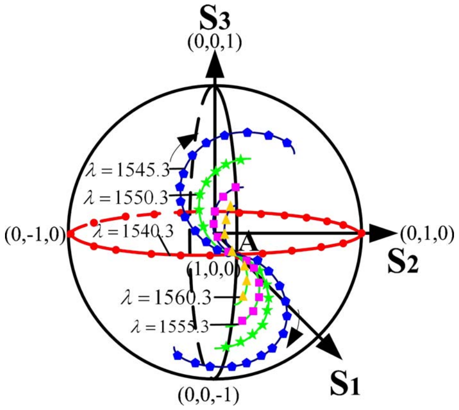

FIG. 5. (Color online) Experimental results of the polarization-state evolution for different wavelengths linearly polarized along the *Z* axis. Under a given external electric field, in the vicinity of the QPM wavelength, a slight drift of wavelength will cause tremendous variance of the output state. However, when the change in the wavelength is large enough, the polarization evolution of the output light tends to be less sensitive to the electric field but swag around in the vicinity of the incident state.

$\Delta\beta=0$ and, at a given small κ, a tiny change in the wavelength which enables $\Delta\beta\neq 0$ will lead to a notable change in the beat length, which consequently results in the tremendous change in the output state of polarization. The QPM wavelength here is actually a critical instable point. But if the variance of wavelength is large enough the evolution gradually becomes less sensitive to the electric field, and if $\Delta\beta$ is so large a small change in κ will have little impact on the beat length or the output state.

In fact, we describe a phenomenon that shows potential of manipulating the polarization states with the advantages of being compact and fast, and with low loss, low driven electric field, and high precision. In the experiment, the azimuth angle of the linearly polarized light can be modulated with the precision of 0.04° and the repeatability is also very high. Compared with some polarization techniques [30,31], the greatest advantage of the PPLN system here is the "low driven electric field and high precision." For example, in the technique proposed by Thaniyavarn [30], the driven electric field (E_2) on the TE-TM conversion is about 7.66 V/μm and in our technique it is around 0.12 V/μm, which is much smaller than the former. Moreover, the TE-TM conversion efficiency of the former technique is about 99.95% while in our technique it is around 99.999 95%, which is much higher than the former. However, the former technique also has some advantages over our technique such as independence on the operating wavelength and less sensitivity to the temperature.

Recently, the periodically poled domain structure in the waveguide has been successfully proposed, which has the advantages of being compact, with low driven external voltage, can easily be integrated, and with fine control [32,33]. It is likely that such a polarization technique based on the periodically poled ferroelectric domain structure will contribute to progress of many fields in future.

In conclusion, we first systematically investigate the polarization behavior of the electromagnetic waves with arbitrary wavelengths in a periodically poled ferroelectric domain structure, which has filled the vacancy of the investigation of the NQPM wavelengths. We discovered that, for the QPM wavelength, the evolution of the polarization is circling along a closed circular path parallel to the equator of the Poincare sphere. But for the NQPM wavelengths the evolution will split into the discrete paths [34]. The QPM wavelength is also found as a critical instable point, where a small change in the wavelength will cause a large effect on the output state. Moreover, by changing the incident state of polarization, sorts of different styles of path can be achieved. The experiment agrees well with both the coupled-mode theory and the Jones matrix method, which can be taken into account to study the behavior of polarization of other structures or materials. We believe that this work will trigger a wide range of interest and open a perspective toward the QPM technology.

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[34] See EPAPS Document No. E-PLRAAN-80-207911 for the evolution of optical polarization on the Poincare sphere for QPM and NQPM wavelengths. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.