Dislocation Parity Effects in Crystals with Quadratic Nonlinear Response

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The effect of edge topological dislocations on the phase matching spectrum of quadratic nonlinear photonic crystals was studied theoretically and experimentally. We have found that the parity of the dislocation's topological charge governs the transfer of energy between an input wave and its second harmonic. A dislocation with an odd topological charge nulls the efficiency of the otherwise optimal phase matched wavelength, whereas high conversion is now achieved at new wavelengths that exhibited low efficiency without the dislocation. However, when the topological charge is an even number, the dislocation has a negligible effect on the efficiency curve. This effect is observed in periodically poled crystals having a single peak in the phase matching spectrum, as well as in phase-reversed and quasiperiodic nonlinear photonic crystals that are characterized by multiple efficiency peaks, where a dimple is imprinted on each spectral peak.

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Dislocations in crystals and their effects on the properties of materials have been studied extensively in the past. When an acoustic wave, an electron wave, or an optical wave travels through a dislocation in a crystal, its effect can be imprinted on the wave front. For example, when an ultrasound pulse is reflected from a rough surface, the scattered wave train contains dislocations [1]. The medium which scatters that wave may exhibit nonlinear response, and in this case scattered waves at harmonics of the input frequency can be observed. In this Letter we study the effect of a dislocation on the harmonically scattered wave. We concentrate on a scattering medium with quadratic nonlinearity, and examine the effect of the topological dislocation on the efficiency of generation of second harmonic radiation. Dislocations were studied so far in optical structures that exhibited a different type of nonlinearity—photorefractive nonlinearity [2–4]—but in that case there are only waves at a single frequency.

Recently, dislocations were introduced into quadratic nonlinear photonic crystals, i.e., crystals in which the quadratic nonlinear coefficient is modulated in an ordered fashion [5–8]. These dislocations can be divided into two different categories: continuous defects which are present along the entire crystal axis [5,6] and local defects [7,8]. The continuous defects have been studied in several configurations of the periodic grating, including tilt, stair, and well dislocations [5,6]. Local defects were studied by varying the thickness of a single domain in the middle of a periodic grating [7]. Another type of local defect is edge dislocation. In this case, the second order nonlinear coefficient has a fork-shaped form and the dislocation is characterized by the topological charge, which is the difference between the number of modulation cycles of the nonlinearity with and without the dislocation. By sending a pump beam transversely to the plane of the dislocation, a vortex beam was generated at the second harmonic (SH), whose orbital angular momentum was determined by the crystal [8].

Here we study for the first time a different case, in which the pump beam travels longitudinally, in the plane of the dislocation. This configuration is commonly used for efficient conversion of a fundamental pump wave to its second harmonic: Owing to dispersion, there is an inherent phase mismatch between the two waves, but the missing momentum can be provided by the nonlinear crystal through quasiphase matching [9,10]. In this case efficient conversion at a certain wavelength is obtained by periodically modulating the sign of the nonlinear coefficient. This concept can be further extended by methods such as phase reversal [11] or quasiperiodic modulation [12,13] that can simultaneously phase match several different processes. Here we show that when a dislocation is added, the phase matching spectrum changes dramatically: Specifically, when a dislocation with an odd topological charge is introduced, the conversion efficiency at the otherwise phase matched wavelength drops to nearly zero. Moreover, optimal conversion is achieved at new wavelengths, which exhibit low efficiency without the dislocation. This behavior is observed not only in periodically poled crystals, but also in quasiperiodic nonlinear photonic crystals, where a dip is imprinted on each spectral peak. Surprisingly, none of these changes in the phase matching spectrum occur for dislocations with even topological charge.

The second-order nonlinearity susceptibility of a periodic structure with an edge dislocation can be written as

$$\chi^{(2)}(X, Y) = 2d_{ij}\mathrm{sgn}[\cos(2\pi X/\Lambda + l\varphi)], \quad (1)$$

where d_{ij} is an element of the quadratic susceptibility $\chi^{(2)}$ tensor, Λ is the quasiphase matching modulation period, l is an integer number that represents the topological charge of the dislocation, and $\varphi = \arctan(X/Y)$ is the azimuthal angle between the propagation direction (X axis of the crystal) and one of its perpendicular directions (Y axis). Note that when $l = 0$ (i.e., no dislocation) a simple periodic modulation is obtained.

The nonlinear coupling between the fundamental and second harmonic waves is described by a set of two coupled-wave equations. Under the assumption of a slowly varying envelope for the fundamental and SH beams of A_ω and $A_{2\omega}$ respectively, these equations are

$$\frac{\partial A_\omega}{\partial X} + \frac{(\frac{\partial^2}{\partial Y^2} + \frac{\partial^2}{\partial Z^2})A_\omega}{2ik_\omega} = \frac{i\omega^2\chi^{(2)}(X, Y)}{k_\omega c^2} A_{2\omega}A_\omega^* e^{-i\Delta kX} \quad , \quad (2a)$$

$$\frac{\partial A_{2\omega}}{\partial X} + \frac{\left(\frac{\partial^2}{\partial Y^2} + \frac{\partial^2}{\partial Z^2}\right)A_{2\omega}}{2ik_{2\omega}} = \frac{i(2\omega)^2\chi^{(2)}(X, Y)}{k_{2\omega}c^2} A_\omega^2 e^{i\Delta kX} , \quad (2b)$$

where k_ω, $k_{2\omega}$ are the wave vectors of the fundamental and SH waves, ω is the radial frequency of the fundamental wave, and $\Delta k = 2k_\omega - k_{2\omega}$ is the phase mismatch. Here we suppose that the nonlinear coupling is weak; hence, the pump intensity is assumed to be constant and therefore we consider only the second equation which describes the evolution of the SH beam.

We have prepared several different crystals with nonlinear modulation patterns that include an edge dislocation by electric field poling of stoichiometric lithium tantalite (SLT); see the Supplemental Material [14] for the fabrication details. The crystal surfaces were then selectively etched in order to reveal the modulation of the nonlinear coefficient. Figures 1(a)–1(d) illustrate some of the fabricated patterns; they consist of periodic nonlinear photonic crystals structures with a period of 21 μm and dislocations corresponding to topological charges of $l = 1$, 2, 3, and 11.

The nonlinear conversion efficiency of these crystals was measured using the experimental setup shown in Fig. 2. The setup is described in the Supplemental Material [14].

Measurement of the four periodically poled crystals with edge dislocations are shown in Figs. 1(e)–1(h), and are compared to numerical simulation based on a split-step beam propagation code [15], and using the Sellmeier equation of [16]. Whereas a periodically poled crystal exhibits a central peak [its location is marked with an arrow in Figs. 1(e)–1(h)], when a dislocation with an odd topological charge is introduced, the conversion efficiency curve changed dramatically. It now exhibits a dip in the

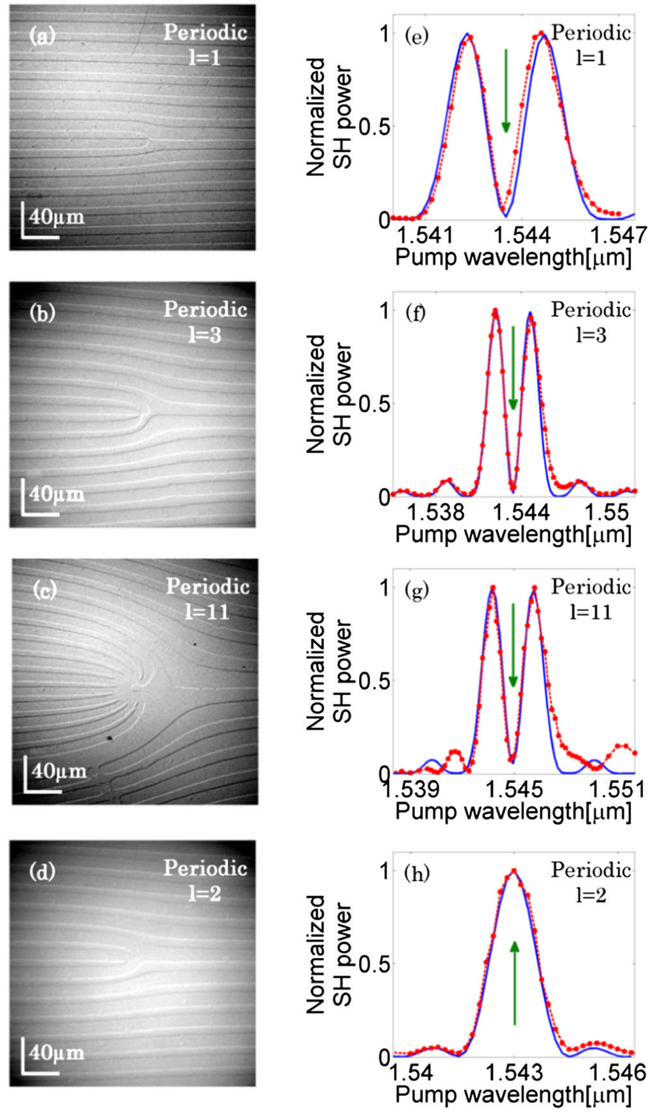

FIG. 1 (color online). Periodic structures with edge dislocations. (a)–(d) Microscope pictures of the crystals. (e)–(h) Comparisons between measured (red dots) and simulated (blue line) results. The green arrows mark the optimal phase matching wavelength without dislocation.

efficiency at the otherwise optimal phase matching wavelength. Moreover, two new efficiency peaks now emerge, located symmetrically below and above it. This phenomenon is observed in the simulations, as well as in the measurements. It is interesting to note that the efficiency curve for the three different cases with odd topological charge (of $l = 1$, 3, and 11) has nearly the same shape. We can conclude that the efficiency spectrum is nearly independent of the topological charge, provided that this charge is an odd number. However, as can be seen from Fig. 1(h), there is a significant difference between dislocations with odd charge and even charge. The conversion efficiency curve of periodic structure with topological charges of $l = 2$ has the same central peak as that of a structure

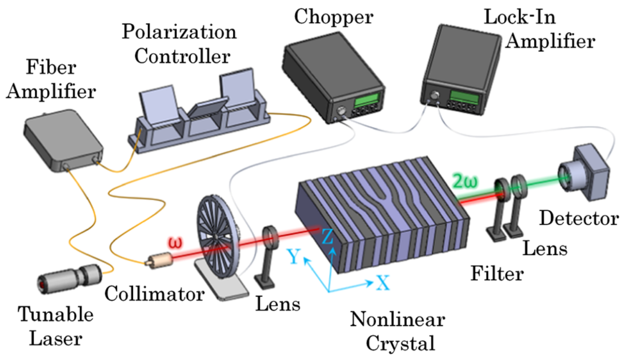

FIG. 2 (color online). The experimental setup.

without the dislocation. We verified by numerical simulations that the same shape is also obtained with higher even values of the topological charge.

In order to compare between the measurement and simulation in Figs. 1(e)–1(h), we had to shift down the simulation curve by ∼6 nm. We assume that this wavelength shift is caused by inaccuracies in the Sellmeier coefficient and the crystal operating temperature. The highest measured second harmonic power of 250 nW was obtained at a wavelength of ∼1543 nm with a pump power of 25 mW in the $l = 2$ case, but similar second harmonic power levels were measured for the crystals with odd dislocations. The measured power is lower by a factor of ∼3 with respect to numerical simulation for parameters that are identical to those of the experiment. The difference is probably caused by deviations of the electric-field poled crystal from the designed nonlinear modulation pattern.

The difference between even and odd dislocations can be understood by examining Eq. (1), the expression for the second-order nonlinearity susceptibility. Near the center of the crystal ($X \approx 0$), the nonlinear coefficients in the upper and lower parts of the crystal for Z polarized pump and SH waves are described by $d_{33}\mathrm{sgn}[\cos(2\pi X/\Lambda)]$, $d_{33}\mathrm{sgn}[\cos(2\pi X/\Lambda \pm l\pi)]$, respectively. Hence, for odd l the nonlinearity of the upper part has opposite sign with respect to the lower part, and therefore by integrating over the entire interaction length we obtain destructive interference for the wavelength which was phase matched without the dislocation. However, when the topological charge l is even, the upper and lower parts of the crystal have the same sign, and therefore we obtain constructive interference. This explains why the efficiency drops to zero at the originally phase matched wavelength only in odd dislocation structures. It is interesting to note that the effect of the localized dislocation is still observed at the exit of the crystal, where the periodic modulation pattern is almost fully recovered. Another way to understand these results is based on the two-dimensional Fourier transform relation between the structure and the second harmonic wave [17,18], as shown in the Supplemental Material [14]. The parity dependence is a property of the Fourier transform of the structure itself. It is therefore a universal result that can be observed even without a nonlinear response of the medium: Similar parity dependence would occur in every system in which the scattered field depends on the Fourier transform of the structure.

In the case of odd topological charge, two new efficiency peaks were formed. The nonlinear process for these peaks is not perfectly phase matched and depends on the interaction length. Without the dislocation the second harmonic power rises till the center of the crystal, and then, owing to the phase mismatch, the energy flows back to the fundamental wave and the second harmonic power drops to nearly zero at the exit of the crystal. However, the dislocation disturbs this otherwise destructive interference process near the central part of the crystal, and as a result a significant power of the second harmonic is obtained at the exit of the dislocated crystal. These phenomena are evident in Figs. 3(a)–3(c) which show the evolution of the generated SH along the crystal. As can be seen in Fig. 3(a), the SH beam power (at the optimal phase matched wavelength without the dislocation) monotonically increases at the first half of the crystal, but at the second half of the crystal, the beam decays to zero owing to the above-mentioned destructive interference effect. However, in the case of even topological charge ($l = 2$), Fig. 3b, we get constructive buildup of the SH beam along the entire crystal, despite the presence of the dislocation at the center. We also examined one of the two new peak wavelengths (1549 nm) for the $l = 1$ case, as shown in Fig. 3(c). In this case the dislocation enables us to obtain a constructive buildup of the SH beam at the exit of the crystal.

The effect of dislocations is not limited to periodic structures. Here we have also introduced dislocations into

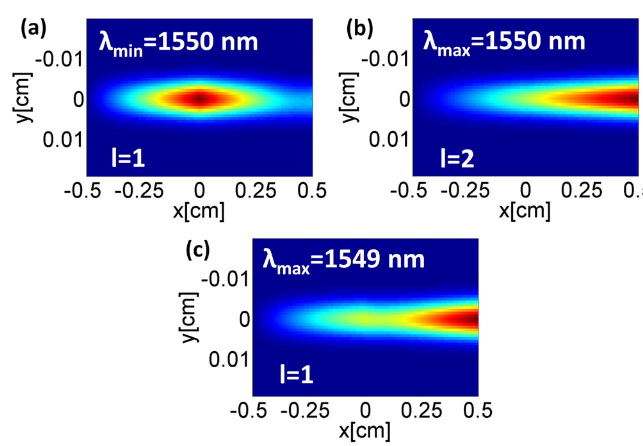

FIG. 3 (color online). The evolution of the generated SH intensity along the dislocated periodic structures for maximum (1550 nm) and minimum (1549 nm) wavelengths. (a) Destruction of SH intensity at 1550 nm for odd topological charge $l = 1$. (b) Constructive buildup of SH intensity at 1550 nm for even topological charge $l = 2$. (c) Recovery of the SH intensity at 1549 nm for odd topological charge $l = 1$.

two types of aperiodic structures, namely, phase reversed [11] structures and quasiperiodic [10,12,13] structures. These structures (without the dislocation) are commonly used to simultaneously phase match several nonlinear processes.

The phase reversed structure is obtained by multiplying two periodic binary structures, as shown schematically in Fig. 4(a). As the name implies, a change in sign of the longer periodicity (Λ_L) structure reverses the phase of the shorter periodicity (Λ_S) pattern. The Fourier spectrum of this structure exhibits two dominant peaks at $2\pi/\Lambda_S \pm 2\pi/\Lambda_L$, as seen in Fig. 4(a). Our design was based on a structure with $\Lambda_S = 21\ \mu$m, $\Lambda_L = 100\Lambda_S$, which can efficiently phase match two different pump wavelengths at 1.54 and 1.556 μm. Edge dislocations with topological charges of $l = 1$, 3 were inserted into this structure, and SLT crystals were poled according to these designed patterns. The measured and simulated second harmonic spectra are shown in Figs. 4(c) and 4(d). The dislocation splits each one of the two peaks in the efficiency curve into two separate peaks. As in the case of a periodic structure, dips in the efficiency are observed at the otherwise two optimal phase matching wavelengths.

Another method to simultaneously phase match several processes is based on quasiperiodic modulation [12,13] of the nonlinear coefficient. Several studies were made in recent years on the observation and characterization of dislocations in quasicrystals [2,3]. Here we consider for the first time dislocations in quadratic nonlinear quasicrystals. For designing the quasiperiodic structure we applied de Bruijn's [19] dual grid method. In our case, we would like to phase match two second harmonic generation processes with pump wavelengths of 1540 and 1560 nm. By applying a one dimensional version of the dual grid method we obtain a quasiperiodic sequence of two building blocks labeled A and B with lengths of 10.5 and 11.0 μm, as illustrated in Fig. 4(b). This one-dimensional quasicrystal has the desired wave vectors in its reciprocal lattice, as shown in Fig. 4(b). A nonlinear quasiperiodic crystal is obtained by modulating the nonlinear coefficient in the A and B blocks to be negative and positive, respectively. An edge dislocation with $l = 1$ was then added to this structure. The designed structure was realized by electric field poling in SLT. Figure 4(e) shows the measured and simulated phase matching spectrum. As in the previous cases, we got destructive interference for the otherwise phase matched wavelengths that caused each one of the two main lobes of the efficiency curve to split into two lobes.

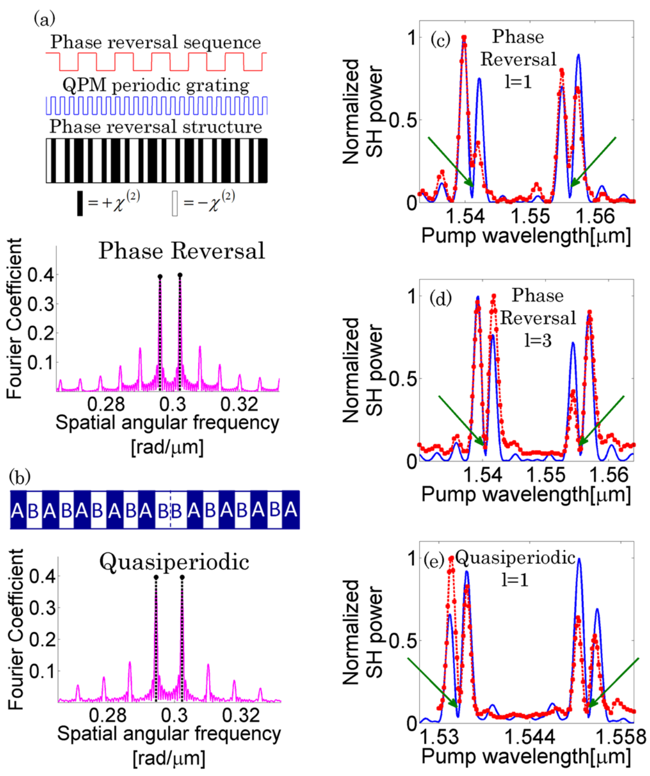

FIG. 4 (color online). The phase reversal and quasiperiodic structures. (a)–(b) Schematic diagram of the proposed structures without the dislocation and the Fourier coefficients of the spatial angular frequency. (c)–(e) Comparisons between measured (red dots) and predicted (blue line) results. The green arrows mark the optimal phase matching wavelengths without dislocation.

We simulated the two non-periodic structures with an even dislocation, having a topological charge of $l = 2$. The same parity effect was observed here; i.e., when the charge is even the efficiency curve is practically unchanged.

In conclusion, we studied the nonlinear scattering process within various nonlinear photonic crystals that have dislocations. We examined periodic, quasiperiodic, and phase reversal structures and found that oddly charged dislocation which was added to these structures stamps its fingerprint in every efficient conversion SH wavelengths of the original structures. The effect of the dislocation is still observed after propagating a very long distance in the crystal (e.g., the light exits the crystal 238 unit cells after the dislocation in the periodic crystal, and the periodic modulation pattern is almost fully recovered). The odd dislocation caused destructive interference in these wavelengths, and the appearance of new efficient conversion SH wavelengths. We also observed that in the case of dislocation with even topological charge, the efficient conversion curve stays the same as in the structure without the dislocation. We note that there are very few known physical systems that present such a clear dependence on parity. One such textbook system is that of a quantum particle in a box, in which the amplitude of the wave function is zero at the center for all the even solutions and reaches its maximum value for all the odd solutions.

The nonlinear photonic crystal provides a flexible platform for studying the effects of dislocations in nonlinear systems. A straightforward extension would be to study the effect of dislocations in two-dimensional nonlinear photonic crystals [20,21]. Moreover, whereas here we considered only a single dislocation having an integer value of its topological charge, it would be interesting to study the cumulative effect of multiple dislocations as well as the influence of fractional topological charge [22]. In addition, while here we used rather low pump intensities, at higher intensities the generated second harmonic wave will be backconverted to the fundamental wave, as described in Eq. (2). In such cases, we expect to observe the effect of the dislocation on the input wave, despite the fact that the dislocation occurs only for the quadratic nonlinear function.

The effects we studied here are not limited only to optical waves. We expect that similar behavior will be observed for other types of waves that are nonlinearly scattered from a dislocation, such as fluid waves [23], acoustic waves [24], matter waves, or electromagnetic waves at different spectral ranges. Furthermore, since the scattered wave is determined by the Fourier transform of the structure, we will observe similar parity dependence in other systems that obey a Fourier transform relation between the scattering structure and the scattered wave. Finally, whereas here we considered quadratic nonlinearities, it would be interesting to examine the effect of dislocations on materials that exhibit higher order nonlinearities, and, in particular, third order nonlinearity.

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