Omnidirectional phase matching of arbitrary processes by radial quasi-periodic nonlinear photonic crystal

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We investigate second-harmonic generation in a nonlinear photonic crystal having radial quasi-periodic order and continuous rotational symmetry. This device enables us to simultaneously phase match different nonlinear interactions in any arbitrary direction of propagation. We have fabricated such a crystal by electric field poling of a magnesium-doped stoichiometric $LiTaO_3$ and demonstrated frequency doubling of two different pump wavelengths at three different angles. Fourier coefficients were 10 times higher than that of a lattice-based multidirectional frequency doubler. © 2010 Optical Society of America

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Periodic [1–3], quasi-periodic [4–6], and random (or short-range order) [7–9] quadratic nonlinear photonic crystals have been studied extensively in recent years. Among them, a special family is that of radially symmetric photonic structures [10–12]. In contrast to the more common lattice-based photonic crystals, the radially symmetric structures can easily support nonlinear interactions in different propagation angles. The simplest member of this family, the annular periodic structure, was realized in a stoichiometric $LiTaO_3$ (SLT) crystal [10] and was used for second-harmonic generation (SHG) in longitudinal and transverse configurations for nonlinear generation of Bessel beams [13] and for the study of nonlinear diffraction effects [14,15]. More sophisticated rotationally symmetric structures—having nonperiodic radial dependence, as well as discrete rotation symmetry—were analyzed in [12].

In this Letter, we present the what we believe to be first realization and experimental characterization of a rotationally symmetric photonic structure with quasi-periodic radial dependence, as depicted in Fig. 1. It consists of a series of concentric rings with an alternating sign of the second-order nonlinearity, where the radial dependence is given by a quasi-periodic sequence. This structure is an omnidirectional multiple wavelength frequency converter; i.e., it efficiently doubles the frequency of several different pump wavelengths in any direction of operation. The only requirement is that the beams should pass through the center of this radial structure.

The structure we study here is quite different from lattice-based structures. A quasi-periodic lattice-based SHG fan was analyzed in [6] and experimentally demonstrated in [16]. The lattice-based structures can also support collinear SHG of several wavelengths in several directions; however, they are limited only to discrete directions. In addition, as the number of desired compensation directions is increased, the conversion efficiencies of each process are diminished, i.e., energy distributes between processes as expected by the Fourier energy theorem. Another interesting alternative is to use short-range ordered samples [11], but the broader angular and spectral acceptance is accompanied by a reduction of conversion efficiency. In contrast to these prior works, the omni-directional multiwavelength doubler studied here can operate at any direction of propagation and its efficiency is much higher. The Fourier efficiency coefficients of the quasi-periodic annular structure we study here are 10 times higher than those of the lattice-based SHG fan [16]. Because both crystals were made of the same material (SLT) and had the same 1 cm length, it was also interesting to compare the actual experimental conversion efficiency. We obtained twenty-four-fold improvement with respect to the lattice-based SHG fan.

The quasi-periodic radial structure that was manufactured and studied is presented in Figs. 2(a) and 2(b). This structure was constructed in order to phase match two arbitrary collinear SHG processes of two wavelengths, 1535 and 1565 nm. As illustrated in Fig. 2(c), if the two Ewald spheres [2] E_a and E_b intersect with rings at the Fourier space G_a and G_b, the interaction is phase matched. The quasi-periodic structure was designed to contain the exact two rings G_a and G_b, which compensate the phase mismatches of the two nonlinear collinear processes. The experimental and simulated diffraction patterns shown in Figs. 2(e)–2(g) exhibit a Fourier spectrum that, indeed, contains the two close rings G_a and G_b.

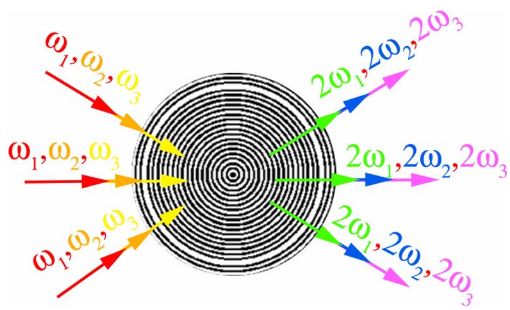

Fig. 1. (Color online) Top view of multicolor SHG fan quasi-periodic-radial nonlinear photonic crystal, which is an SHG fan for several arbitrary frequencies. The black and white circles denote areas with positive and negative second-order nonlinearity.

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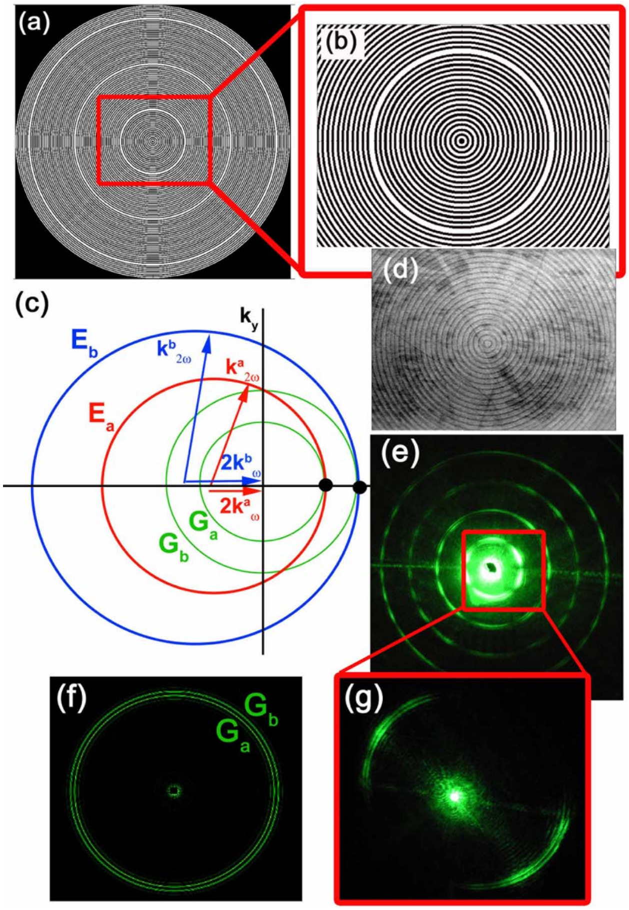

Fig. 2. (Color online) Quasi-periodic-radial nonlinear photonic crystal. (a), (b) Geometric structure. The black and white areas represent the sign of the nonlinear coefficient. (c) Phase matching occurs when Ewald spheres E_a or E_b intersect with a circle on Fourier space. The black dots mark these intersection points. (d) Microscope image of the crystal. (e) Linear diffraction of the crystal and expanded view of central part in (g). (f) Numerical simulation of the structure's spectrum: two rings that were designed to phase match two processes.

There were two steps in the construction of the device. The first step was planning the one-dimensional (1D) basic structure. This structure was designed to compensate two phase mismatches of two SHG processes at 1535 and 1565 nm at an operating temperature of 100 °C. The phase mismatches of these two nonlinear processes for magnesium-doped stoichiometric $LiTaO_3$ are $\Delta k_a = 2.9543 \times 10^5$ [1/m] and $\Delta k_b = 3.0734 \times 10^5$ [1/m], respectively. The 1D quasi-periodic structure is depicted in Fig. 3(a). It was planned with the dual grid method [6]. This method provides a systematic algorithm to design a nonlinear photonic quasi-crystal whose reciprocal lattices contain an arbitrary set of desired wave vectors. The building blocks of the structures were $\Lambda_1 = 10.2$ μm and $\Lambda_2 = 10.6$ μm. The duty cycles that gave the highest Fourier coefficients were 0% and 100%, respectively; i.e., the first building block will have only negative nonlinearity, whereas the second building block will have only positive nonlinearity, as depicted in Fig. 3(a). The Fourier coefficients for the two desired processes were 0.35 and 0.36, as presented in Fig. 3(b). The second step was to span the quasi-periodic radially by converting each linear stripe

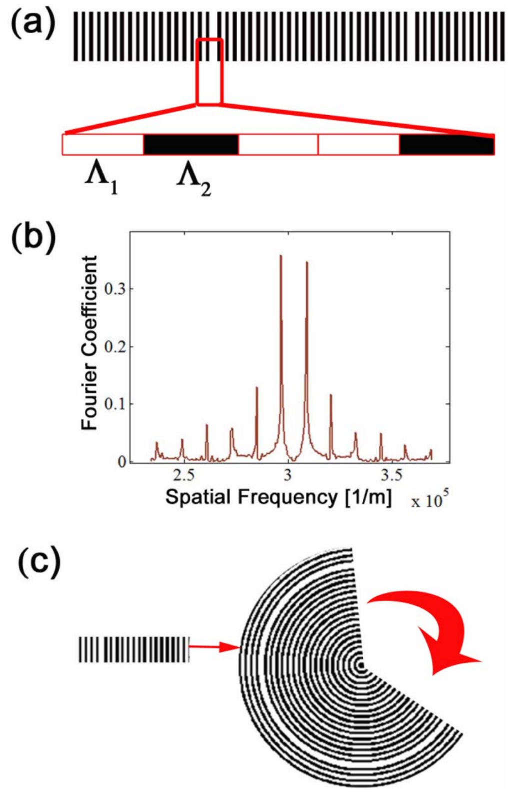

Fig. 3. (Color online) Constructing a quasi-periodic-radial nonlinear photonic crystal. (a) Construction of a 1D quasi-periodic structure. (b) Fourier spectrum of the 1D quasi-periodic structure. (c) Spanning the 1D structure into a quasi-periodic-radial nonlinear photonic crystal.

to a circle with a corresponding radius, as depicted in Fig. 3(c).

The 1-cm-long, 0.5-mm-thick crystal was electric field poled according to this design. The crystal was held on a temperature-controlled mount. We first tested its temperature dependence by focusing an 1565 nm pump beam, from an external cavity diode laser, into a waist size of 30 μm at the center of the crystal. The beam was polarized along the Z direction of the crystal. The measured temperature dependence, shown in the inset of Fig. 4,

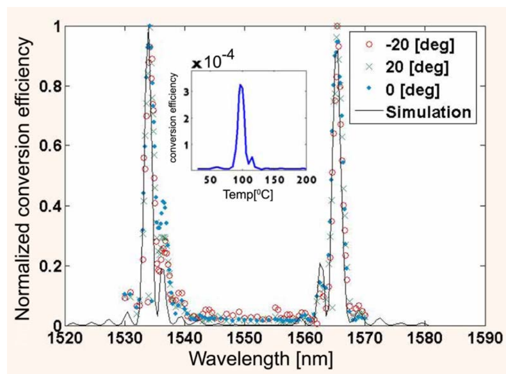

Fig. 4. (Color online) Experimental results of the multicolor SHG fan. Normalized SHG efficiency as a function of wavelength. The solid curve is a numerical simulation, and the markers are the experimental collinear SHG efficiency versus wavelength for three pump input angles of −20°, +20°, and 0°. Inset, SHG efficiency versus temperature at 1565 nm.

Table 1. Conversion Efficiency of Multicolor SHG Fan

Wavelength (nm), Angle (deg.)	Fourier Coefficient	Experimental Efficiency	Simulated Efficiency
1535, −20	0.36	8.37e − 4 [1/W]	3.05e − 3 [1/W]
1535, +20	0.36	8.94e − 4 [1/W]	3.05e − 3 [1/W]
1535, 0	0.36	8.51e − 4 [1/W]	3.05e − 3 [1/W]
1565, −20	0.35	9e − 4 [1/W]	2.85e − 3 [1/W]
1565, +20	0.35	8.99e − 4 [1/W]	2.85e − 3 [1/W]
1565, 0	0.35	8.05e − 4 [1/W]	2.85e − 3 [1/W]

has the expected peak at 100 °C, as predicted by the design.

Next, we studied the angular and spectral dependence by measuring the SHG efficiency as a function of wavelengths at three representative angles, denoted as −20°, 0°, and +20°, where the angle is measured in air from the normal to the input surface of the crystal. The experimental results are presented in Fig. 4 and in Table 1. They are compared with a numerical split-step beam propagation simulation that assumed the same parameters as those used in the experiment. There is a good agreement between theory and experiment in terms of spectral dependence. The measured conversion efficiency is approximately one-third of the calculated efficiency, owing to small defects in the fabrication. We can see that the device doubles the wavelengths of 1535 and 1565 nm with essentially the same efficiency for different propagation directions. In fact, the efficiency is quite similar for all six different cases shown in Table 1.

A possible application is for such a structure to be placed inside a bow-tie ring resonator. This resonator can be used as an enhancement cavity for cascaded processes, such as generating a third harmonic by cascading SHG and difference-frequency generation. The use of the quasi-periodic radial photonic crystal enables us to phase match the two interactions and, in addition, the beams can pass twice through the crystal in each round trip, thereby making the conversion process more efficient. Ring cavities may also be used in cascaded downconversion, for improving the pump-to-idler conversion [17].

In summary, we have realized and experimentally characterized an omnidirectional, multicolor frequency converter. Compared with the SHG fan reported in [16], we got a tenfold improvement in Fourier coefficients for each one of the two nonlinear processes. Moreover, we demonstrated that this device functions as an efficient SHG fan for two arbitrary wavelengths. In the future, this device can also be used in the transverse configuration [13], in which the beam propagates along the Z axis of the crystal, and may enable nonlinear generation of multicolored Bessel beams.

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References

1. M. Yamada, N. Nada, M. Saitoh, and K. Watanabe, Appl. Phys. Lett. **62**, 435 (1993).
2. V. Berger, Phys. Rev. Lett. **81**, 4136 (1998).
3. A. Arie, N. Habshoosh, and A. Bahabad, Opt. Quantum Electron. **39**, 361 (2007).
4. S. N. Zhu, Y. Y. Zhu, and N. B. Ming, Science **278**, 843 (1997).
5. K. Fradkin, A. Arie, P. Urenski, and G. Rosenman, Phys. Rev. Lett. **88**, 023903 (2001).
6. R. Lifshitz, A. Arie, and A. Bahabad, Phys. Rev. Lett. **95**, 133901 (2005).
7. M. Baudrier-Raybaut, R. Haïdar, Ph. Kupecek, Ph. Lemasson, and E. Rosencher, Nature **432**, 374 (2004).
8. R. Fischer, S. Saltiel, D. Neshev, W. Krolikowski, and Y. Kivshar, Appl. Phys. Lett. **89**, 191105 (2006).
9. Y. Sheng, J. Dou, J. Li, D. Ma, B. Cheng, and D. Zhang, Appl. Phys. Lett. **91**, 101109 (2007).
10. D. Kasimov, A. Arie, E. Winebrand, G. Rosenman, A. Bruner, P. Shaier, and D. Eger, Opt. Express **14**, 9371 (2006).
11. T. Wang, B. Ma, Y. Sheng, P. Ni, B. Cheng, and D. Zhang, Opt. Commun. **252**, 397 (2005).
12. N. Voloch, T. Ellenbogen, and A. Arie, J. Opt. Soc. Am. B **26**, 42 (2009).
13. S. M. Saltiel, D. N. Neshev, R. Fischer, W. Krolikowski, A. Arie, and Y. S. Kivshar, Phys. Rev. Lett. **100**, 103902 (2008).
14. S. M. Saltiel, Y. Sheng, N. V. Bloch, D. N. Neshev, W. Krolikowski, A. Arie, K. Koynov, and Y. S. Kivshar, IEEE J. Quantum Electron. **45**, 1465 (2009).
15. S. M. Saltiel, D. N. Neshev, W. Krolikowski, N. V. Bloch, A. Arie, O. Bang, and Y. S. Kivshar, Phys. Rev. Lett. **104**, 083902 (2010).
16. A. Bahabad, A. Ganany-Padowicz, and A. Arie, Opt. Lett. **33**, 1386 (2008).
17. G. Porat, O. Gayer, and A. Arie, Opt. Lett. **35**, 1401 (2010).