Healing Block-assisted Quasi-phase Matching

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Abstract:
A new QPM structure is proposed to improve the efficiency when the first-order QPM domain length is too short to be fabricated. SHG efficiency 4.69 times higher than the third-order QPM is experimentally demonstrated.

I. Introduction

Engineerable QPM structures have been widely used in many nonlinear optical applications. For example, fan-out and multiple QPM devices are useful in wavelength-tunable optical parametric oscillation (OPO) [1,2]. QPM gratings with and without spatially chirped periods are attractive in ultrashort pulse characterizations [3,4]. User-defined phase-matching spectral grids can be realized by several optimization algorithms, such as simulated annealing [5], genetic algorithm [6], and iterative domino [7]. However, the conversion efficiency of a real QPM device could be subject to the minimum domain length $d_{\min}$ that can be reliably fabricated. In the event of the first-order QPM domain length $d_1<d_{\min}$, a third-order QPM structure with domain length $3d_1$ is commonly used while the conversion efficiency is significantly reduced to $\eta_1/9$ (η_1 is the efficiency of the first-order QPM). In this work, we proposed the healing block (HB)-assisted QPM structure to access the efficiency gap for the first time (to the best of our knowledge). It is found that the efficiency of HB-QPM could be higher than $\eta_1/9$ as long as $d_{\min}< 1.54d_1$. In our experiment, an HB-QPM structure with $d_{\min}=1.08d_1$ achieved 4.69 times higher SHG efficiency than that of a third-order QPM grating of the same length.

II. Theory

An HB-QPM structure is composed of repeated substructures; each consists of M regular domains of constant length d plus one longer "healing block" of length d_{HB} [Fig. 1(a)]. Under the assumption of plane wave and nondepleted pump, the SHG efficiency of an arbitrary QPM grating is

$$\eta=\eta_{norm}\times|G|^2,\ G=\frac{1}{L}\int_0^L g(x)e^{i(\Delta k\cdot x)}dx, \tag{1}$$

where η_{norm} is the normalized efficiency accounting for the input intensity, crystal nonlinearity, and grating length, G is the complex mismatch function value, $g(x)$ denotes the x-dependent domain orientation, and Δk is the wavevector mismatch. In HB-QPM, the complex number G for a substructure is

$$G_{sub}=G_0+G_{M+1}+2\sum_{n=1}^{M}G_n,\ G_n=\frac{e^{i\phi_n}}{\Delta k\cdot L},\ \phi_n=n\pi+\Delta k\cdot x_n. \tag{2}$$

Equation (2) means that the nth domain boundary x_n contributes to G by a complex number $2G_n$ [except for the two end boundaries (n=0, M+1) where the factor of "2" is absent]. For the first M regular domains of length $d=(1+\Delta)d_1$, we got $x_n=n(1+\Delta)d_1$, $\phi_n=n\times\delta$, and the complex numbers G_n, G_{n-1} arising from two adjacent boundaries differ by a constant phase $\delta=\Delta\times\pi$ [Fig. 1(b)]. Summation of these out-of-phased complex numbers $\{G_n\}$ would be negligible. By adding a healing block of proper length d_{HB} to the M regular domains such that $G_{M+1}=G_0$, G_{sub} of every substructure would be identical and can add up constructively [Fig. 1(c), M=1]. The requirement of $G_{M+1}=G_0$, i.e. $\phi_{M+1}=2(M+p+1)\pi$, results in

$$d_{HB}=(2p+1-M\times\Delta)d_1, \tag{3}$$

where p is the smallest positive integer greater than $(M+1)\Delta/2$ such that $d_{HB}>d>d_1$ is satisfied.

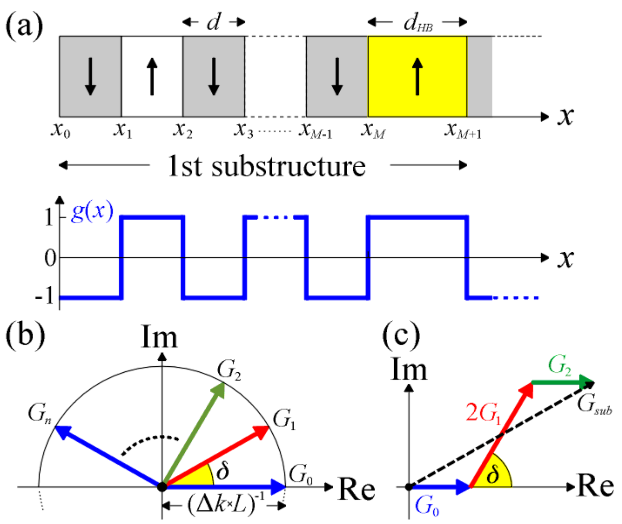

Fig. 1. (Color online) (a) Schematic of HB-QPM and the corresponding domain orientation distribution function $g(x)$. (b) The complex numbers $\{G_n\}$ contributed by regular domains of length $d=(1+\Delta)d_1$, where $\delta=\Delta\times\pi$. (c) The complex numbers $\{G_n\}$ and G_{sub} due to the individual domain boundaries (solid) and the entire substructure (dashed) with M=1.

The SHG efficiency of the HB-QPM normalized to that of the first-order QPM becomes

$$\mu=\left|\frac{G_{sub}}{G_{(1)}}\right|^2=\left\{\frac{1}{M+2p+1}\times\frac{\sin[(M+1)\delta/2]}{\sin(\delta/2)}\right\}^2. \tag{4}$$

Figure 2(a) shows that the optimal number M (solid) decreases with the increase of regular domain length d, for the phase difference δ increases with d and will diminish $|G_{sub}|$ [Fig. 1(c)]. Once the optimal M is obtained, the corresponding healing block length d_{HB} (dotted) is determined by Eq. (3). Figure 2(b) illustrates that the SHG efficiency of HB-QPM (solid) is higher than those of the third-order (dashed-dotted) and second-order (dashed, assuming a duty cycle of 0.25) QPM when the regular domain length is shorter than $1.54d_1$ and $1.23d_1$, respectively.

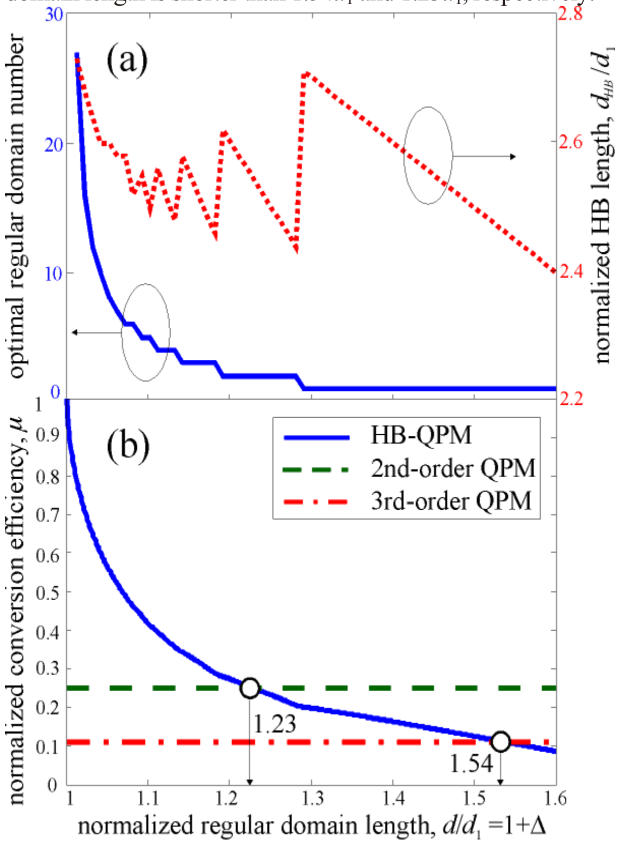

Fig. 2. (Color online) (a) The optimal number of regular domains (solid) and the corresponding normalized healing block length d_{HB}/d_1 (dotted), as well as (b) the normalized conversion efficiency μ (solid) as functions of the normalized regular domain length d/d_1. The efficiencies due to the second-order (dashed) and third-order (dashed-dotted) QPM are also shown for comparison.

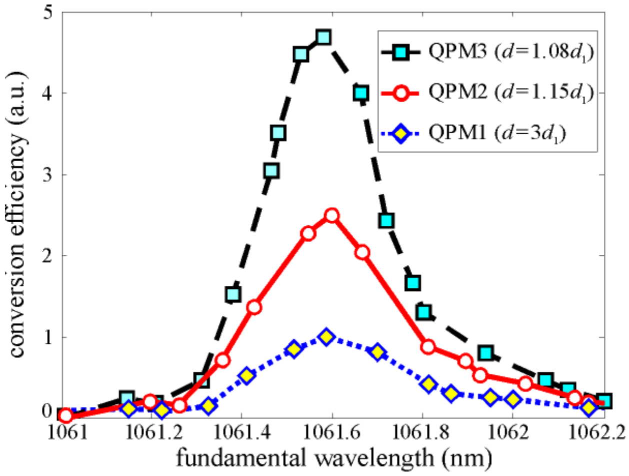

Fig. 3. (Color online) The experimentally measured phase-matching tuning curves of QPM1 (diamonds), QPM2 (circles), and QPM3 (squares), respectively.

III. Experiment

We fabricated a 8-mm-long periodically poled MgO doped lithium niobate (PPMgCLN) chip with three different QPM gratings designed for frequency doubling of 1064 nm (d_1=3.46 μm). The first grating (QPM1) is a third-order QPM with a constant domain length of $3d_1$=10.38 μm. QPM2 and QPM3 are designed by HB-QPM with M=3, d=4.00μm, d_{HB}=8.76μm, and M=5, d=3.75μm, d_{HB}=8.93μm, respectively. The phase-matching tuning curves were measured by a tunable CW laser and a photodetector. Figure 3 illustrates the experimental results. The peak conversion efficiencies of QPM2 (circles) and QPM3 (squares) are 2.50 and 4.69 times higher than that of QPM1 (diamonds).

IV. Conclusion

In summary, we proposed and experimentally demonstrated the HB-QPM structure to enhance the conversion efficiency when the domain length d_1 of the first-order QPM is too short to be reliably fabricated. Our calculation showed that efficiency enhancement over the third-order QPM occurs as long as the regular domain length is shorter than $1.54d_1$. In our experiments, the SHG efficiency of HB-QPM could be 4.69 (2.50) times higher than that achieved by the third-order QPM if the regular domain length d is 1.08 (1.15) times of d_1.

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