Effects of random and systematic perturbations in a one-dimensional photonic crystal wavelength converter

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We study the problem of the tolerance to fabrication errors in one-dimensional photonic crystal wavelength converters. In particular we consider the case of wavelength conversion obtained via quasiphase matching (QPM) based on a periodic amplitude modulation of the fundamental wave (Bloch-mode-QPM). Both numerical simulations of a waveguide-based structure and experimental results in an AlGaAs thin-film multilayer show that the proposed QPM mechanism is extremely tolerant to both systematic and random errors in the periodicity and duty cycle of the grating.

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Thanks to their potentiality in achieving efficient $\chi^{(2)}$ interactions, photonic band-gap (PBG) structures have recently attained considerable attention. In particular, owing to the periodic modulation of the refractive index or geometry of the waveguide, these structures can introduce such an amount of dispersion as to compensate the material one. Moreover recent studies of second-order nonlinear processes in one-dimensional (1D) gratings [1,2] have also been motivated by the possibility of obtaining a simultaneously phase-matched and enhanced nonlinearity near the photonic band-gap edge [3]. It has been shown [4,5] that this enhancement has mainly two origins. The first is that phase matching (dispersive PM) of the nonlinear process is obtained, due to the variation of the phase velocities near the PBG edge [6]. The second reason is that these structures experiment a PBG edge mode-density enhancement corresponding to a modification of the group velocities. In $\chi^{(2)}$ materials, the combination of these two effects may give origin to extremely efficient second harmonic (SH) conversion that may scale up to the sixth power with device length [7]. Although this process might seem very efficient, it presents serious technological difficulties if it has to be implemented in an integrated optical waveguide. It has also been demonstrated that dispersive PM requires very high index contrast in order to compensate the large material dispersion at telecom wavelengths (around 1550 nm) [2]. An example of such an integrated grating is given by Midrio, Socci, and Romagnoli [8], where alternating layers of material with air attains the high index contrast. The main problem with such gratings is due to fabrication error tolerance in the periodicity or duty cycle [8], which becomes extremely critical. The tolerance to random errors in the photonic crystal periodicity is a problem that has been addressed for a waveguide in a 2D photonic crystal [9] and the transmission characteristics were shown to be robust with errors up to 20% of the periodicity. However, nonlinear wavelength conversion introduces a further difficulty as the phase relation between the different interacting wavelengths is of utmost importance. The authors in Ref. [8] observed that even a 0.1% error in the layer dimensions or in the refractive index caused the pump to no longer seed on the designed transmission peak. In this way frequency conversion is ruined because, since the reflectivity of the elementary cell is very high, even a small variation of the layers' thickness prevents the different contributions of transmission and reflection from summing in phase and thus destroying the phase matching condition.

Recently we have demonstrated the possibility of obtaining efficient conversion in a 1D photonic crystal with a different method [10]. It is well known [11] that a periodic perturbation may give rise to quasiphase matching (QPM) if the perturbation wave vector (K) is exactly equal to the optical wave-vector-phase mismatch, i.e., $K=2\pi/\Lambda=2k_{\omega}-k_{2\omega}$ (where Λ is the perturbation periodicity). However, we have shown [10] that when we also consider the finite length of the perturbation (i.e., the grating), the situation is slightly more complex so we analyzed it in a different manner. For clarity we briefly recall the main aspects of this phase-matching method. The generated SH field may be written as

$$E_{2\omega} \propto \int_0^L f(z)\chi^{(2)}E_{\omega}^2\exp(-j\Delta\beta z) \qquad (1)$$

where L is the crystal length, $\chi^{(2)}$ is the second-order nonlinearity, $\Delta\beta=\beta_{2\omega}-2\beta_{\omega}$ is the phase mismatch, and z is the propagation axis. If $\Delta\beta$ is finite, the SH energy flows back and forth between the fundamental (FF) to the SH waves, thus greatly limiting the conversion efficiency. $f(z)$ is a generic periodic function and is usually thought of as a periodic modulation of the material nonlinear coefficient so as to render the energy flow unidirectional from the FF to the SH field, i.e., so as to give rise to quasiphase matching (QPM) [12]. The periodicity is chosen to be an even multiple of the

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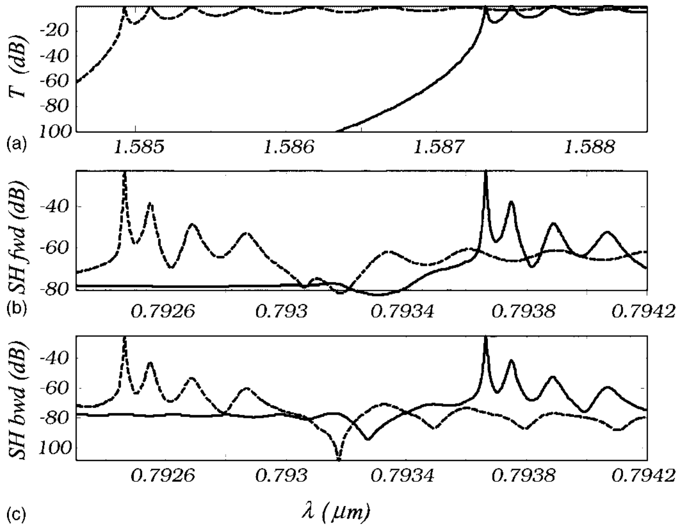

FIG. 1. Top graph: linear transmission of the FF field near the band edge. Middle and bottom graphs: SH efficiency in the forward and backward directions, respectively. Results obtained for a 111 unit cells grating and other parameters as indicated in Ref. [10] without errors (dashed line) and with a 2 nm systematic error on the period length (solid line).

coherence length $l_c = \pi/\Delta\beta$ over which the FF and SH waves fall out of phase. In Ref. [10] we propose a periodic modulation of the fundamental field amplitude rather than of the nonlinear coefficient — as can be seen from Eq. (1) the result is identical. This can be achieved in photonic crystal. Indeed Bloch modes are the natural modes of a periodic crystal structure and represent stationary wave oscillations with a periodicity equal to that of the crystal. If the periodicity of the crystal is chosen to be an even multiple of l_c we find that the incoming plane wave undergoes a stationary amplitude modulation such that the nonlinear interaction is quasiphase matched. In Ref. [10] we described a mesa waveguide photonic crystal in AlGaAs based on the described Bloch-mode QPM (BM-QPM). We shall consider the same crystal in this work, namely a multilayered structure with refractive index contrast of 0.18 and 0.03 for the FF and SH, respectively, and a unit cell made of a succession of layers $(5b-a-5b-a-5b-3a)$ with lengths $a=154$ nm and $b=227.2$ nm The nonlinearity was taken as 100 pm/V. The total unit cell length is made to be equal to 4 l_c and the particular substructure of the cell is chosen so as to position a photonic bandgap edge at the peak wavelength. This gives a further enhancement of the conversion efficiency due to the mode density enhancement. A crystal with 111 unit cells (463 μm total length) is theoretically able to deliver a -21 dB (10%/W) conversion efficiency with a 50 mW pump in a 1 μm^2 mode-area waveguide. One of the main advantages of such a grating structure is the possibility to use a much lower index contrast between adjacent layers (0.2 or less) with respect to the high index contrast gratings required for dispersive PM. This in turn allows for a greater flexibility in the choice of materials and waveguide configurations while still maintaining a relatively high nonlinear coefficient of the order of 30 pm/V or higher in AlGaAs.

The majority of the structures proposed in literature are double resonant (DR), i.e., both FF and SH waves are tuned to PBG edges, in order to have a greater enhancement in the density of modes. Considering a single-resonant (SR) PBG, this would present much better tolerances to fabrication errors compared to double-resonant (DR) PBGs. However, the index contrast required for a SR PBG that is in perfect PM is too high to be implemented with currently available technologies in an AlGaAs-integrated waveguide. We, therefore, propose a quasiphase-matched structure with lower index contrast and hence lower conversion efficiency/mm. This in turn requires a longer grating for which tolerances are still a problem to verify. Hence in this report we present an analysis on the tolerances to fabrication errors of the waveguide structure described above and the experimental results obtained from a thin-film sample, designed with the same rules used for obtaining the BM-QPM in the mesa waveguide, in which we found layer-thickness errors. In order to have a complete analysis of tolerances to fabrication errors of the waveguide structure, we calculate the conversion efficiency in the SH generation process for two different types of possible fabrication errors: a systematic error on the period and a random error on the duty cycle. This analysis was carried out using the transfer matrix formalism described for example in Ref. [13] and is particularly indicated for the study of 1D multilayered structures with random fluctuations. To evaluate the tolerance to a systematic error, we start from the described optimized structure and vary the period Λ (i.e., $a+b$), maintaining the other simulation parameters identical. As an example, Fig. 1 shows the results evaluated for the 111 cell grating [10]. The dashed line shows the linear transmittance and SH conversion efficiencies in the backward and forward directions for the structure with no errors on layer thickness. The solid line is relative to a $\Delta\Lambda \simeq 2$ nm systematic error in the grating periodicity (hence an error of $\sim$700 nm on the total grating length). We observe that such an error, thanks to the SR structure, induces only a shift $\Delta\lambda \simeq 2.5$ nm of the band edge, but the conversion efficiency remains unchanged. The impact of a random fluctuation in the duty cycle is evaluated considering a random error with a Gaussian distribution with standard deviation σ for different values of σ. The results are summarized in Fig. 2. We examined trends for three different parameters: wavelength where maximum conversion occurs, conversion efficiency, and conversion bandwidth. In Fig. 2 we show both the average (over 20 separate simulations for each value of σ) and the standard deviation from the average value, which are represented respectively by the points and the error bars.These results point out that although we find a sensitive decrease in the effi-

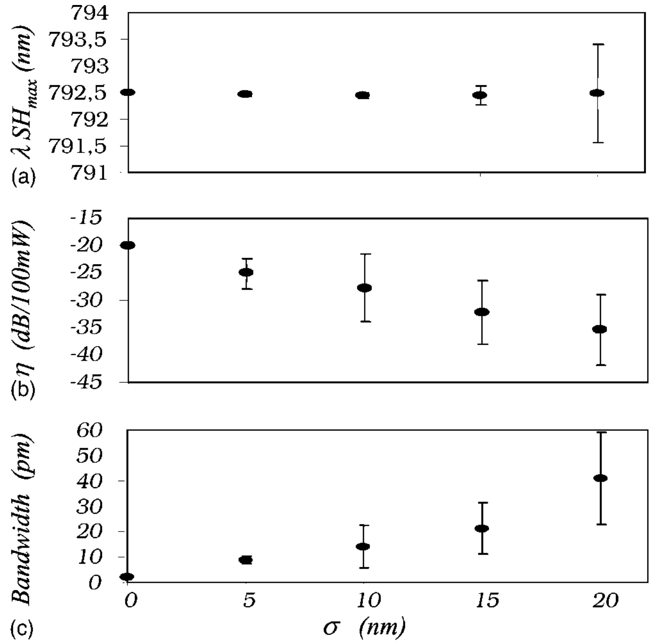

FIG. 2. Tolerances to fabrication errors: (a) variation of the wavelength at which maximum conversion occurs, (b) variation of the conversion efficiency, and (c) variation of the bandwidth of conversion. Results, showed in terms of mean value and variance, are obtained repeating the simulation for 20 times for each value of the standard deviation σ of the random error Gaussian distribution.

ciency, such as 8 dB for σ=10 nm, the device still shows efficient SH generation if compared to a non-phase-matched medium that would give a maximum conversion efficiency of −70 dB. As the intensity peak of SH decreases (with increasing σ), we observe a consequent increase of the conversion bandwidth while the wavelength where maximum conversion occurs is practically unchanged. These results show that BM-QPM-based structures are much more tolerant to fabrication errors with respect to deep gratings. Furthermore there is no clear threshold, i.e., a point after which the nonlinear process suddenly breaks down, but rather a continuous deterioration with increasing σ. In order to experimentally evaluate the effect of fabrication errors we first measured, the experimental setup used is shown in Fig. 3, a multilayered structure, also shown in the inset, made of alternating layers of $Al_{0.3}Ga_{0.7}As/Al_{0.7}Ga_{0.3}As$, so that the index contrast at fundamental frequency is $\delta n_{\omega}=0.18$. The multilayer sample was deposited by metal organic vapor phase epitaxy (MOVPE) using a horizontal silica reactor with the capacity of one 2-in.-wafer. The reagents were trimethylgallium (TMG), trimethylaluminium (TMA), and Arsine using a growth temperature of 740 °C. The structure was deposited using constant TMG and TMA flows to define $Al_{0.3}Ga_{0.7}As$ with $Al_{0.7}Ga_{0.3}As$ created by adding additional TMA. The periodicity is formed by five unit cells, each made of ten layers with thickness (126-118-126-118-126-118-126-118 -379-118) nm so that the total grating length is 7.4 μm. The sample is a 2-in.-wafer and the deposition process leads to a varying thickness across the wafer, i.e., to a varying systematic error in the multilayer periodicity. Figure 4 represents the theoretical linear transmission and reflected SH. The SH peak conversion efficiency appears near the photonic band-gap edge. Note that there is a slight shift in the position of the SH peak wavelength with respect to the FF transmission peak. This is due simply to the QPM mechanism, based on the BM-amplitude modulation of the fundamental field (band-gap mode density enhancement is irrelevant in this case due to the overall small reflectivity). For the experiment we used a 110-fs transform-limited pulse train (80 MHz repetition rate) generated by an optical parametric oscillator. The source is tunable between 1400 and 1600 nm and the reflected SH power is monitored in function of the incident FF wavelength. Figure 5 shows the measured FF transmission and the reflected SH (normalized with respect to the background noise). With respect to Fig. 4 we note a large 30-nm shift in the FF transmission peak position. We obtained a good fit of this curve by introducing systematic errors in both the periodicity and the duty cycle of the periodic structure. The best fit was obtained with a unit cell with (145-108-145-108-145-108-145-108-340-108) nm layer thicknesses. Introducing a further random error in the duty cycle with σ equal to 3% of the layer thickness does not substantially change the result. We underline that, rather than

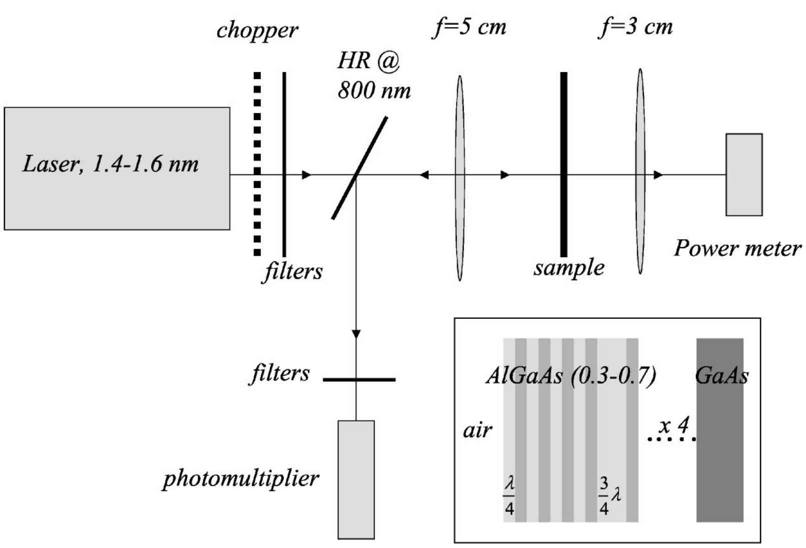

FIG. 3. Experimental setup: the laser is focused on the sample, showed in the inset, by use of a lens. The SH generated in reflection is collected on a photomultiplier whereas the power meter placed behind the sample (shown in detail in the inset) registers the linear transmission.

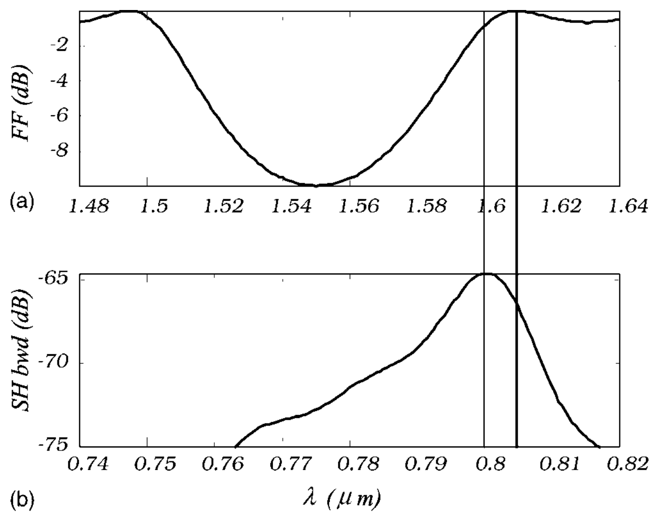

FIG. 4. Theoretical results: (a) linear transmission of the FF field near the band edge and (b) SH efficiency in reflection. Results are obtained for the multilayered structure presented in the inset of Fig. 3.

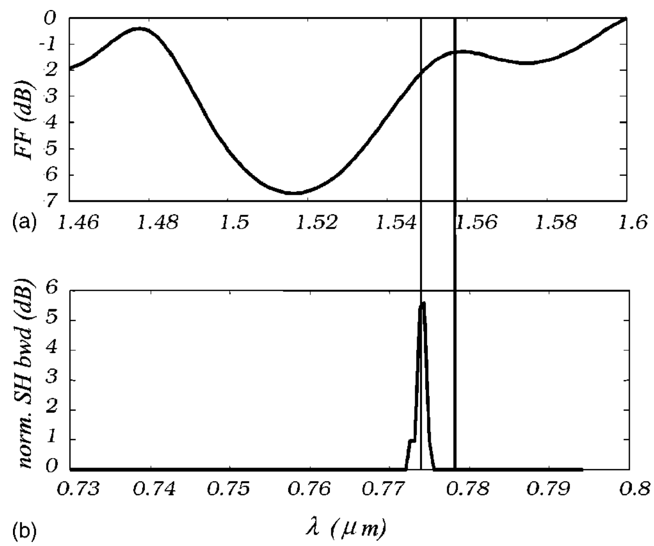

FIG. 5. Experimental results for (a) FF field and (b) SH field in the backward direction.

the overall total conversion efficiency or shape of the curves, the most important result in Fig. 5 is the robustness of the generated SH that still retains the main features of the simulated ideal structure. Indeed, notwithstanding the large difference between the ideal and the actual true structure, both the SH amplitude and the offset of the peak wavelength with respect to the FF transmission peak remain of the same order of magnitude.

In summary we have analyzed the tolerance to fabrication errors of a 1D PBG frequency converter based on the BM-QPM mechanism presented in [10]. This analysis is of fundamental importance for the final working device and indeed represents the main limitation of integrated PBG converters based on high-index contrast gratings. The proposed quasiphase-matched structure does not rely on the strong effective index variation near the PBG edge (property extremely sensitive to small errors), but rather on the amplitude modulation of the FF field due to the shape of the Bloch modes near the band edge—a much more robust effect. We have proved this point both theoretically and experimentally. A possible drawback of this approach could be the slower SH growth versus grating length with respect to that shown in deep grating structures. However, in the extremely high efficiency of the deep grating structures lies also their weakness, i.e., the low tolerance to fabrication errors. Moreover BM-QPM does theoretically allow an efficient employment of the AlGaAs nonlinearity with effective nonlinearities higher than 30 pm/V [10]. Even assuming losses as high as 1 dB/mm we expect conversion efficiencies of the order of −2 dB in less than 2 mm with a 50 MW/cm^2 input pump intensity. If we also account for random fluctuations in the structure with $\sigma=10$ nm then the conversion efficiency is reduced to the still acceptable value of −10 dB.

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[1] A. V. Balakin, V. A. Bushuev, N. I. Koroteev, B. I. Mantsyzov, I. A. Ozheredov, A. P. Shkurinov, D. Boucher, and P. Masselin, Opt. Lett. **24**, 793 (1999).
[2] Y. Dumeige, P. Vidakovic, S. Savauge, I. Sagnes, J. A. Levenson, C. Sibilia, M. Centini, G. D'Aguanno, and M. Scalora, Appl. Phys. Lett. **78**, 3021 (2001).
[3] M. Scalora, M. J. Bloemer, A. S. Manka, J. P. Dowling, C. M. Bowden, R. Viswanathan, and J. W. Haus, Phys. Rev. A **56**, 3166 (1997).
[4] J. W. Haus, R. Viswanathan, M. Scalora, A. Kalocsai, J. D. Cole, and J. Theimer, Phys. Rev. A **57**, 2120 (1998).
[5] M. Centini, C. Sibilia, M. Scalora, G. D'Aguanno, M. Bertolotti, M. J. Bloemer, C. M. Bowden, and I. Nefedov, Phys. Rev. E **60**, 4891 (1999).
[6] A. Yariv and P. Yeh, J. Opt. Soc. Am. **67**, 438 (1977).
[7] Y. Dumeige, I. Sagnes, P. Monnier, P. Vidakovic, C. Meriadec, and A. Levenson, J. Opt. Soc. Am. B **9**, 2094 (2002).
[8] M. Midrio, L. Socci, and M. Romagnoli, J. Opt. Soc. Am. B **19**, 83 (2002).
[9] T. N. Langtry, A. A. Asatryan, L. C. Botten, C. M. de Sterke, R. C. McPhedran, and P. A. Robinson, Phys. Rev. E **68**, 026611 (2003).
[10] D. Faccio, F. Bragheri, and M. Cherchi, J. Opt. Soc. Am. B **21**, 296 (2004).
[11] N. Bloembergen and A. J. Sievers, Appl. Phys. Lett. **17**, 483 (1970).
[12] M. M. Fejer, G. A. Magel, D. H. Dieter, and R. L. Byer, IEEE J. Quantum Electron. **28**, 2631 (1992).
[13] Y. Jeong and B. Lee, IEEE J. Quantum Electron. **35**, 162 (1999).