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Invited Paper

Blue and green light emission: New directions and perspectives of applications of one-dimensional photonic band gap structures

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ABSTRACT

Nonlinear quadratic interactions near the band edge of a finite length photonic band gap structure are studied .A strong enhancement of the nonlinear response is found due to the essential role played by the electromagnetic density of modes and phase matching conditions . This open the door to a new generation of very compact nonlinear devices . The blue and green light emission conditions are discussed

Keywords: Photonic devices, optics , nonlinear optics

1. INTRODUCTION

The past two decades have witnessed an intense investigation of electromagnetic wave propagation phenomena at optical frequencies in periodic structures. Usually referred to as photonic band gap (PBG) crystals [1], the essential property of these structures is the existence of allowed and forbidden frequency bands and gaps, in analogy to the allowed and forbidden energy bands and gaps of semiconductors. Many applications have been envisioned in one-dimensional systems, which usually consist of multilayer, all-dielectric stacks. These applications include: a nonlinear optical limiter [2] and a diode [3], a photonic band edge laser [4]; a true-time delay line for delaying ultra-short optical pulses [5]; a high-gain optical parametric amplifier for nonlinear frequency conversion [6]; and more recently, transparent metal-dielectric stacks [7]

Some demonstrations of the potential of these structures have been made recently with the realization of photonic crystal fibers [8] and in the microwave regime, with the development of a PBG structure for applications to antenna structures [9] From a theoretical, more analytical point of view, the study of nonlinear optical interactions in PBG structures has been undertaken mainly in regard to soliton-like pulses (often referred to as gap-solitons) in cubic $\chi(3)$ [10], and quadratic $\chi(2)$ media [11] within the context of one-dimensional multilayer stacks.

One of the most intriguing aspects related to the $\chi(2)$ response of PBG crystals that still remains unresolved is the possibility of greatly enhancing the conversion efficiency of nonlinear processes. The enhancement of second harmonic generation (SHG) is perhaps the best example that we could cite, although in general our discussion is valid for multi-wave mixing processes. The processes that we discuss owe their increased efficiency to the simultaneous availability of (1) exact phase matching conditions, and (2) high localization of the fields with frequencies tuned at transmission resonances near the photonic band edge. These conditions were first reported in ref.6, where it was numerically demonstrated that pumping a 20-periods GaAs/AlAs multilayer stack approximately 5 microns in length with a 3 micron pulse could generate short, picosecond SH pulses tuned at a wavelength of 1.5 microns, with power levels enhanced by two to three orders of magnitude with respect to the output from an equivalent length of an exactly and ideally phase-matched bulk GaAs (or AlAs) substrate.

Recently, we theoretically investigated the possibility of nonlinear intensity dependent phase shifts in a structure similar to that of ref.6. Our results showed that nonlinear phase shifts of order π could be obtained in a structure only 7 microns in length, with threshold intensities of a few tens of MW/cm2 12. Also recently, a theoretical description based on the introduction of an effective index was used in ref.13 in order to help explain the results of ref.6. It was found that the geometry of the structure introduces an effective dispersion that can mediate nonlinear up-conversion processes under conditions of strong field localization and exact phase matching. From the experimental point of view, Balakin et al. 14 have provided preliminary experimental evidence of enhancement of SHG near the photonic band edge under conditions similar, but not exactly the same as those discussed in refs.6 and 13. The authors reported nearly 300 times better conversion efficiency for the generation of a SH signal near the band edge of a ZnS/SrF multilayer stack [14]

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Recently a theoretical approach based on the multiple scale expansion theory [15] has shown in a more formal way how phase matching conditions and strong field localization are responsible for the enhancement of nonlinear interactions near the band edge.

The aim of this work is to extend the results discussed in refs.6 and 13 to the very important spectral region of the blue and green by taking advantage of the dispersive properties of PBG structures close to the band edge.

2. PHASE- MATCHING CONDITIONS

A necessary condition for efficient nonlinear coupling in any kind of quadratic material is the fulfilment of phase matching. For bulk materials, this condition is satisfied when the phase velocity of the fundamental wave (FF) equals the phase velocity of the second harmonic wave (SH) fields. In finite PBG structures, phase matching conditions for second harmonic generation have been recently addressed with the introduction of an effective index [13]. We begin by writing the complex transmission coefficient for the structure:

$$t(\omega)=x(\omega)+i\,y(\omega)=\sqrt{T}\,e^{i\phi_t} \tag{1}$$

where:

$$\phi_t = tg^{-1}(y/x) \pm m\pi \tag{2}$$

is the total phase accumulated as light propagates through the medium. The transmission $t(\omega)$ can be easily calculated using the well-known matrix transfer method. ϕ_t contains all the information relating to the layered structure, such as refractive indices, number of layers, and layer thickness. The integer m is uniquely defined assuming $\phi_t(\omega)$ is a monotonically increasing function, and the condition that $m=0$ as $\omega \rightarrow 0$ is satisfied. Beginning with the analogy of propagation in a homogeneous medium, we can express the total phase associated with the transmitted field as:

$$\phi_t = k(\omega)L = \frac{\omega}{c} n_{eff}(\omega)L \tag{3}$$

where $k(\omega)$ is the effective wave vector, and consequently n_{eff} is the effective refractive index that we attribute to the layered structure whose physical length is L.

Recasting the transmission function in the form $\sqrt{T} = |t| = e^{-\alpha L}$, implies that an incident field of unit amplitude is attenuated by an amount $e^{-\alpha L}$, where $\alpha=(\omega/c)n_i$, and n_i is the imaginary component of the index. Rewriting $\sqrt{T} = e^{\ln\sqrt{T}}$, the complex transmission coefficient becomes $t = e^{\ln\sqrt{T}} e^{i\phi_t} = e^{i\phi} = x+iy$. Therefore,

$$i\phi = i\phi_t + \ln\sqrt{T} = i\left(\frac{\omega}{c}\hat{n}_{eff}L\right) \tag{4}$$

where we still have $\phi_t = tg^{-1}(y/x) \pm m\pi$ as before. Eq.(3) then becomes:

$$\hat{n}_{eff}(\omega) = (c/\omega L)\ [\phi_t - (i/2)\ln(x^2+y^2)]. \tag{5}$$

Eq.(5) suggests that at resonance, where $T=x^2+y^2=1$, the imaginary part of the index is identically zero. We may also define the effective wave-vector as:

$$\hat{k}(\omega) = \frac{\omega}{c}\hat{n}_{eff}(\omega). \tag{6}$$

Once the effective index has been defined, Eq.(6) represents the *effective* dispersion relation of the layered structure. In Figure 1 we show the transmission coefficient for a 20-period structure of the kind discussed in Ref. 6 (upper curve) and the imaginary part of the effective index (lower curve). In Figure 2 we plot the real part of the index. We note that the real part of the index displays anomalous dispersion inside the gap. The imaginary component is small and oscillatory in the pass-bands; it attains its maximum at the middle of each gap, where the transmission is a minimum, and it is identically zero at each transmission resonance, as expected.

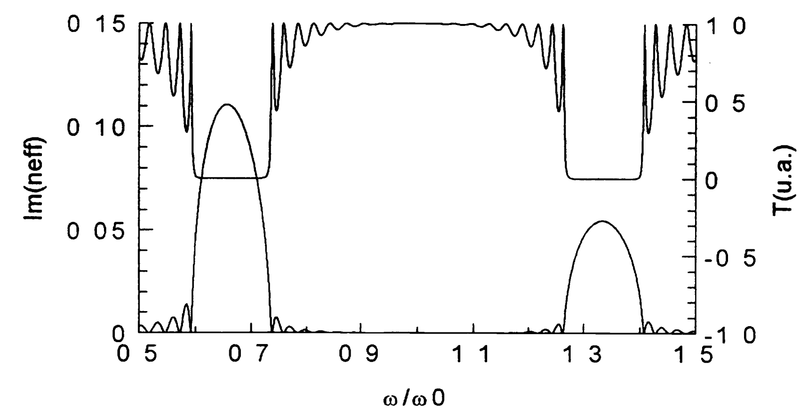

Figure 1. Transmission spectrum vs normalized frequency for a 20-period structure, half/quarter- wave stack (upper curve) The indices of refraction are n_a=1 and n_b=1 42857. The layers have thicknesses $a=\lambda_0/(4n_a)$ and $b=\lambda_0/(2n_b)$, λ_0 =1μm, $\omega_0=2\pi c/\lambda_0$. Imaginary part of the effective index (lower curve).

In Figure 2 the real part of the effective index is given for a 2, 10, 20-periods and for an infinite structure. This figure suggests that the effective, dispersive properties of the structures are modified by the number of periods, and converge to the infinite-structure results increasing the number periods.

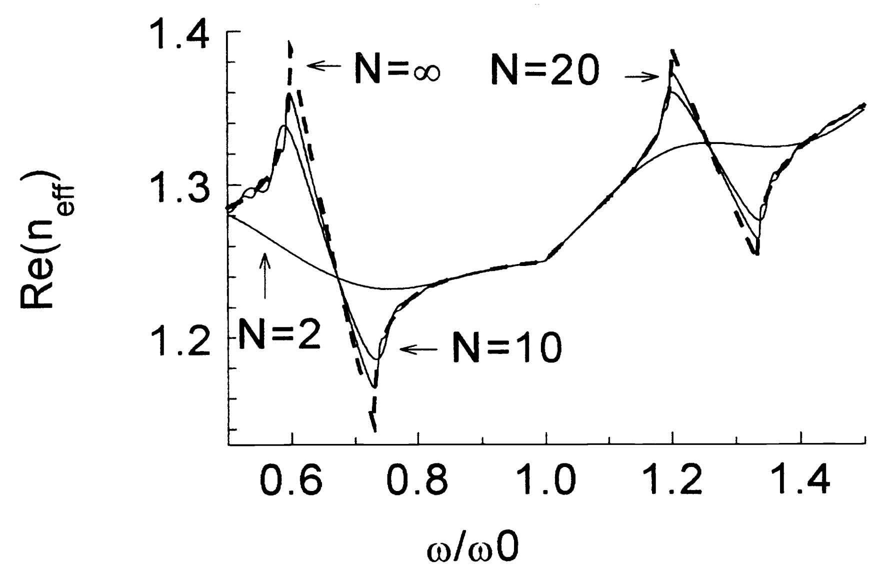

Figure 2. Real part of the effective index for a 2, 10, and 20-period structure (continuous curves); dispersion relation for the infinite structure (dashed line).

The phase matching conditions are realised when the " phase" velocities of the interacting fields are equal. The "phase velocities" are calculated through the " effective index " and the effective wave vector [13,15]. For a second harmonic generation process in a nonlinear periodical structure as the one described for the figure 1, the phase matching condition is realised tuning the fundamental field at the low frequency band edge and the second harmonic at the second resonance close to the next band gap .

In analogy with the group velocity defined for the infinite structure, we may also define the group velocity for the finite PBG structure as:

$$\hat{V}_g = \mathrm{Re}\left[\left(\frac{d\hat{k}}{d\omega}\right)^{-1}\right] \tag{7}$$

and the density of modes (DOM) as its inverse

$$\hat{\rho}_g = \mathrm{Re}\left[\left(\frac{d\hat{k}}{d\omega}\right)\right] \tag{8}$$

In Figures 3 we show the group velocity(a) and the DOM (b) for the 20-period structure of Figure1. The anomalous dispersion inside the band gap (see Figure 2) is responsible for the superluminal tunneling . It has also been experimentally demonstrated that this formalism is valid outside the band gap, where incident short pulses display significant slowing down5 At the first transmission resonance near the band edge, we note that group velocity is a minimum, this corresponds to a maximum value for the DOM This effect is due to the high localization of the field inside the structure [15]

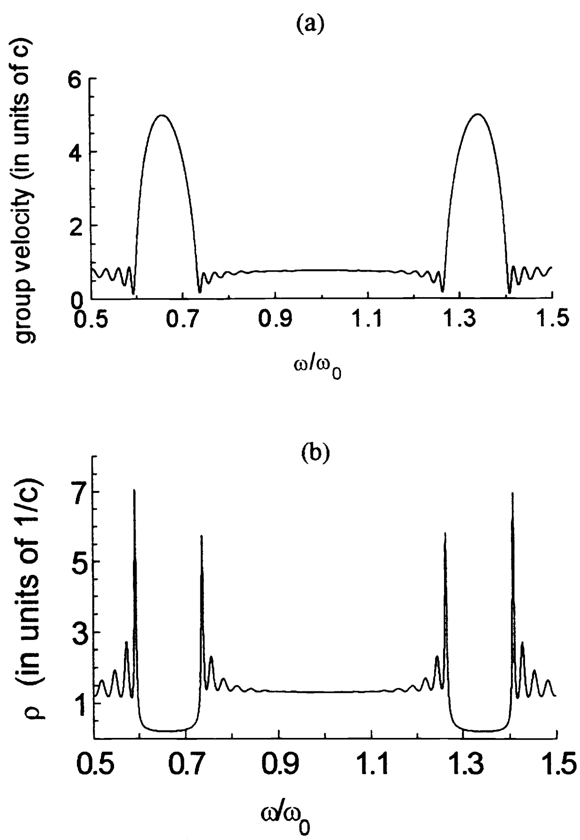

Figure 3 (a) Group velocity and (b) density of modes ρ for the PBG structure of Figure1 Note that the group velocity becomes superluminal inside the gaps.

3. ENHANCEMENT OF QUADRATIC INTERACTIONS NEAR THE PHOTONIC BAND EDGE

As we have mentioned above, one of the most surprising effects in a finite PBG structure is the possibility of greatly enhancing the quadratic response with respect to an equivalent length of perfectly phase matched bulk material, provided the FF and SH frequencies are tuned near the first and the second–order band edges, respectively. This phenomenon was first predicted by direct integration of the equations of motion in ref.6. The numerical integration of Maxwell equation's in the regimes described above provides a unique tool for the practical scope of designing devices for optimized up and down-conversion based on one-dimensional PBG structure[5]. However through a suitable application of the multiple scale expansion theory it is possible to describe the nonlinear quadratic interaction in the multilayer structure in a very interesting form, reducing the field dynamics to a set of first order nonlinear differential equations for the slowly varying envelopes A_1 and A_2, being the subscript 1 referred to the pump field at the fundamental frequency, and 2 for the second harmonic generated field

$$\frac{\partial A_1}{\partial z_1} = i\frac{\tilde{\omega}_{1,m}}{\tilde{V}_E^{(1,m)}}\gamma_1 A_2 A_1^* \quad , \tag{9a}$$

$$\frac{\partial A_2}{\partial z_1} = i\frac{\tilde{\omega}_{2,n}}{2\tilde{V}_E^{(2,n)}}\gamma_2 A_1^2 \quad . \tag{9b}$$

The coefficient $\tilde{V}_E^{(j,k)}$, γ_1, and γ_2 are defined as follows

$$\tilde{V}_E^{(j,k)} = \frac{-ic^2\int_0^L \tilde{\Phi}_{j,k}^* \frac{d\tilde{\Phi}_{j,k}}{dz_0} dz_0}{\tilde{\omega}_{j,k}\int_0^L \varepsilon_j(z_0)\left|\tilde{\Phi}_{j,k}\right|^2 dz_0} \quad , \quad j=1,2 \tag{10}$$

$$\gamma_1 = \frac{\int_0^L [\tilde{\Phi}_{1,m}^*]^2 d^{(2)}(z_0)\tilde{\Phi}_{2,n} dz_0}{\int_0^L \varepsilon_1(z_0)\left|\tilde{\Phi}_{1,m}\right|^2 dz_0} \quad , \tag{11}$$

$$\gamma_2 = \frac{\int_0^L \tilde{\Phi}_{2,n}^* d^{(2)}(z_0)\tilde{\Phi}_{1,m}^2 dz_0}{\int_0^L \varepsilon_2(z_0)\left|\tilde{\Phi}_{2,n}\right|^2 dz_0} \quad ,$$

where ε_j is the dielectric function at the fundamental (j=1) and second harmonic frequency (j=2), $d^{(2)}$ is the quadratic coupling function, $\{\tilde{\Phi}_{j,k}$ is the set of eigenfunctions which describe the field spatial distribution inside the PBG, z_1 is the spatial variable related to the total geometrical dimension of the PBG (slowly variable) , z_o is the fast variable related to the "true" geometrical spatial distribution of the layers oscillation [12,15]. Field localisation effects and phase matching conditions are embedded in the energy velocity V_E and in the effective coupling coefficients γ_1 and γ_2 .

As an example, let us calculate the solutions of the eqs. (9) for the SH transmitted field, in the undepleted pump approximation. We find.

$$I_2^T = \frac{8\omega^4 \left(I_1^I\right)^2}{\varepsilon_0 c^5} L^2 \left| \frac{\int_0^L \tilde{\Phi}_{2,n}^* d^{(2)}(z_0)\tilde{\Phi}_{1,m}^2 dz_0}{\int_0^L \tilde{\Phi}_{2,n}^* \frac{d\tilde{\Phi}_{2,n}}{dz_0} dz_0} \right|^2 \tag{12}$$

From Eq. (12), we observe that in a PBG structure the SH intensity scales as the square of the length L^2, multiplied by an overlap factor that itself scales as a power of the length. This should be compared with a bulk material, where the SH intensity scales as the square of the length. Under exact phase matching conditions, the SH eigenmode is tuned at the second peak of transmittance, away from the second band edge . It is possible to demonstrate[15] the following scaling law for the SH signal transmitted from the PBG structure :

$$I_2^T \approx N^6 \tag{13}$$

where N is the number of periods of the structure.

This is a general property of the second harmonic generation in the undepleted pump approximation for a PBG structure when the FF field is tuned to the peak of transmittance near the band edge, and the SH field is phase matched.

We may now apply the above considerations to the design of a new type of blue laser that could operate in the 400nm range, based on a one-dimensional PBG structure. The device is composed of 30-periods alternating SiO_2/AlN layers, to form a quarter-wave/ half-wave stack similar to that described in the previous sections. With a reference wavelength of 0.52 microns, the total length of the PBG structure is approximately only 6 microns. The AlN layers are assumed to have a nonlinear coefficient approximately equal to 10pm/V. The FF beam is assumed to be incident at an angle of 30^0 degrees with respect to the normal to the surface of the structure. The FF frequency at 800nm is tuned as previously discussed, i.e., at the first transmission resonance near the first order band gap; the SH frequency is tuned at 400nm, which corresponds to the second resonance peak near second order gap. We note that we are using experimentally available data for both materials, and that aligning the resonance as prescribed can be done by varying the thickness of the layers, i.e., by adjusting the effective dispersion of the structure [13].

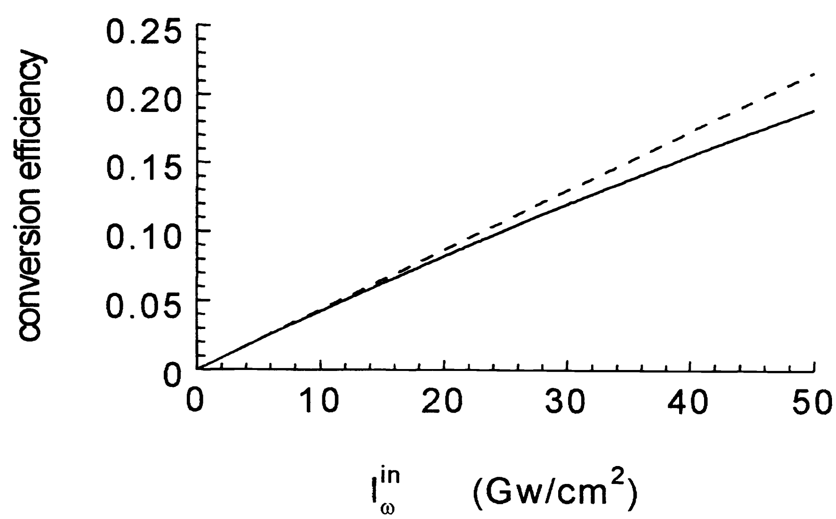

Figure 4 Second harmonic conversion efficiency vs the input pump intensity under undepleted pump approximation (dotted line) and in the case of pump depletion (continuous line) . A conversion efficiency of approximately 15% is reached for input pump intensity of 40GW/cm^2.

The structure is exactly phase matched according to ref. 13. Using Eqs.(9) and (13) we calculate the SH intensity as function of the input FF intensity we calculate the SH intensity as function of the input FF intensity, and show the results in Figure (4). We find a conversion efficiency of approximately 15% in a *single pass* through the device, with input power levels of 40GW/cm^2. We stress that the structure is only 6 microns of length. These results are confirmed by the direct numerical integration of the dynamical equations of motion, using the beam propagation method discussed in ref 6· the conversion efficiency obtained numerically is almost identical to what predicted by the model.

As another example we consider the symmetric PBG structure composed of 19-periods alternating GaN/$Al_{86\%}Ga_{14\%}N$ layers and final layer of GaN, the thickness of the layers is respectively 135nm for the high index layer (GaN) and 88nm for the low index layer ($Al_{86\%}Ga_{14\%}N$), the total length of the PBG structure is approximately only 4 microns. The $Al_{86\%}Ga_{14\%}N$ layers are assumed to have a nonlinear coefficient approximately equal to 25pm/V. The FF beam is assumed to be incident at an angle of 20^0 degrees with respect to the normal to the surface of the structure. The FF frequency at 1 035μm and the SH are phase matched [13]. As shown in Fig.(5), we find a conversion efficiency of approximately 5% in a *single pass* through the device, with input power levels of 40GW/cm^2.

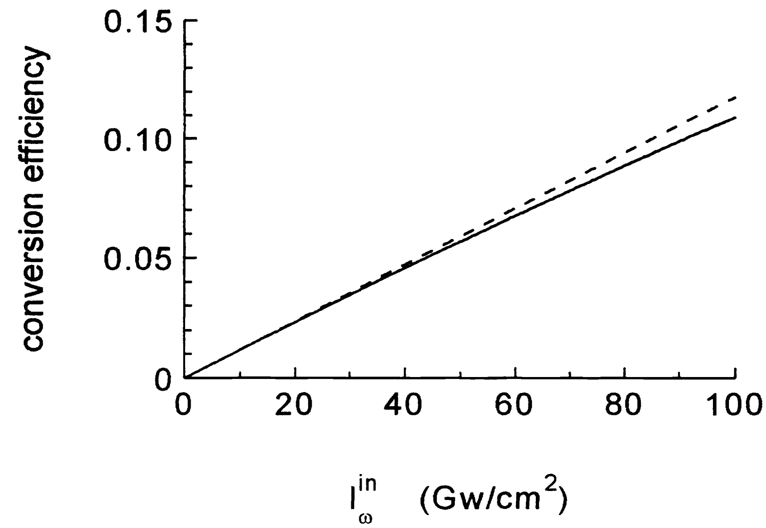

Figure 5 Second harmonic conversion efficiency vs the input pump intensity under undepleted pump approximation (dotted line) and in the case of pump depletion (continuous line) A conversion efficiency of approximately 5% is reached for input pump intensity of 40GW/cm^2.

These examples represent a remarkable improvement with respect to the current state of the art in the field of blue or UV and green light generation. It also shows that PBG structures are probably the most promising structures proposed to date for the efficient generation of short wavelength, blue and green light. For comparison, it was recently reported[16] that 31% blue light conversion efficiency was obtained in a *1cm* sample of quasi-phase-matched Lithium Niobate material, with comparable pump intensities.

4. CONCLUSIONS

In summary, using both numerical integration of the Maxwell equations and a theoretical approach based on the multiple scales expansion it is possible to deep analyse the properties of nonlinear quadratic interactions near the photonic band edge of finite, photonic band gap structures. Enhancement effects near the band edge are entirely due to field localization effects that arise from a reduction of the speed of light inside the structure, and the simultaneous availability of phase matching conditions. The scaling law we analytically obtain in Eq.(13) is confirmed by direct numerical integration of Maxwell's equations. These very promising results pave the way to possible application of PBG structures to new frequency converter devices.

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