Highly efficient second-harmonic generation in doubly resonant planar microcavities

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A theoretical study of second-harmonic generation in planar microcavities with periodic dielectric mirrors is made. Strong enhancement of the nonlinear conversion is predicted when double resonance for the pump and harmonic fields, as well as phase matching, are achieved. For a given structure design, the finite angle of incidence is used as a tuning parameter and the splitting between cavity modes with different polarizations is used to compensate the material dispersion. Examples are given for GaAs cavities with AlGaAs/Alox dielectric mirrors. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1786657]

Frequency conversion in cubic materials like GaAs is limited by the difficulty of achieving phase matching, which is instead easily obtained in birefringent nonlinear materials. Various methods to overcome the short coherence length arising from refractive index dispersion have been proposed and practically realized, including tailoring of photon dispersion relations by a dielectric modulation[1,2] and use of form birefringence in multilayers[3,4] A high efficiency of nonlinear conversion is a key factor for a number of device applications, e.g., for ultracompact, coherent optical sources.

Another possible route for increasing the conversion efficiency for second-harmonic generation (SHG) relies on the use of resonance effects in Fabry–Pérot cavities. Confinement of the electromagnetic field mode at the pump and/or harmonic wave frequencies leads to a strong enhancement of the nonlinear effect depending on the cavity finesse. Single resonance at either the pump or harmonic frequency can be realized in planar microcavities (MCs) with $\lambda/4$ Bragg reflectors. Simultaneous double resonance has been achieved with external-cavity configurations.[5,6] It would be desirable to obtain doubly resonant, highly efficient SHG in monolithic cavities, especially in planar microcavities with dielectric mirrors, which have very high finesse and low losses.[7] A theoretical study of SHG in microcavities with both metallic and dielectric mirrors[8] clarified the conditions to be fulfilled for increasing the conversion efficiency through resonance effects: in particular, when dielectric mirrors are used, the layer thicknesses should depart from the $\lambda/4$ condition (in order to have stop bands for both pump and harmonic fields) and in addition a phase-matching relation should be satisfied. However, working at normal incidence it is difficult to meet all these conditions simultaneously, especially for the lack of a suitable tuning parameter and for the complications introduced by material dispersion which requires the use of a thick cavity.[8] Experimental realization of a doubly resonant $Al_{0.3}Ga_{0.7}As$/AlAs microcavity structure at non-normal incidence has been achieved in Ref. 9 with the use of dual-wavelength nonperiodic dielectric mirrors. Optimization of structures for third-harmonic generation has also been reported.[10]

In this theoretical work we propose an approach for obtaining highly efficient SHG in planar MCs with periodic dielectric mirrors. GaAs cavities with AlGaAs/Alox reflectors are considered. Like in Ref. 9, we use the finite angle of incidence θ as a tuning parameter to achieve double resonance for pump and harmonic waves as well as phase matching: the polarization splitting of the Fabry–Pérot modes plays an important role, as is explicitly shown. The use of periodic mirrors results in a conversion efficiency that increases exponentially with the number of periods in the Bragg reflectors and becomes very large in a highly compact monolithic cavity device.

We consider the symmetric microcavity structure sketched in Fig. 1: a central cavity layer of length L_c is sandwiched between two identical distributed Bragg reflectors (DBRs) with layer thicknesses L_1, L_2 and $N+1$ (N) layers of material 1 (2). The polarizations of pump and harmonic waves at a given angle of incidence θ are taken to be p and s, respectively. Only the cavity layer is assumed to be nonlinear. The dielectric mirrors are characterized by a complex reflection amplitude $\sqrt{R}e^{i\phi}$, where ϕ is the phase, R is the mirror reflectance, and the transmittance $T=1-R$. The cavity enhancement η of SHG is defined as the ratio between the SH power transmitted by the whole structure and the one generated by the isolated nonlinear layer. Neglecting pump depletion, the expression given in Ref. 8 can be generalized to

$$\eta = \left| \frac{T_\omega \sqrt{T_{2\omega}}\{1 + R_\omega \sqrt{R_{2\omega}} \exp(\imath \delta_m)\}}{\{1 - R_\omega \exp(\imath \delta_\omega)\}^2 \{1 - R_{2\omega} \exp(\imath \delta_{2\omega})\}} \right|^2, \quad (1)$$

where

$$\delta_\omega = 2\phi_\omega + 2k_{z,\omega} L, \quad (2)$$

$$\delta_{2\omega} = 2\phi_{2\omega} + 2k_{z,2\omega} L, \quad (3)$$

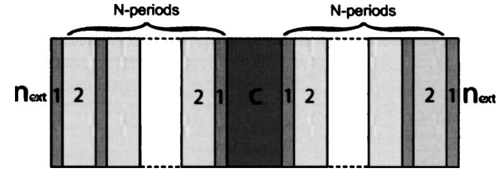

FIG. 1. Schematic layout of the microcavity structure.

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$$\delta_m = \phi_{j,\omega} + \phi_{k,\omega} + 2k_{z,\omega}L + \phi_{i,2\omega} + k_{z,2\omega}L, \tag{4}$$

k_z is the field wave vector along the growth axis z and i, j, k are the Cartesian components coupled by the nonlinear susceptibility $\chi^{(2)}_{ijk}$.[11] The conversion efficiency is maximum when δ_ω, $\delta_{2\omega}$ and δ_m are all multiples of 2π. These conditions correspond to the simultaneous resonance of pump and second harmonic and to an effective phase matching of the cavity. From expressions (2)–(4) it follows that, in a doubly resonant symmetric microcavity (DRM), δ_m can be only an *even* or *odd* multiple of π. In the first case, when $\delta_m = 2n\pi$, $n \in Z$ we have *effective phase matching* and the highest efficiency. In the second case, $\delta_m = (2n+1)\pi$ and the numerator vanishes for $R_{\omega,2\omega} \to 1$: we refer to this situation as *anti-phase matching*. In the limit of high mirror reflectance at both ω and 2ω, the cavity enhancement η becomes

$$\eta_{\text{pm}} \simeq \frac{4}{(1-R_\omega)^2(1-R_{2\omega})}, \tag{5}$$

$$\eta_{\text{apm}} \simeq \frac{1}{4}\frac{(1-R_{2\omega})}{(1-R_\omega)^2}. \tag{6}$$

at the phase matching and anti-phase matching conditions, respectively.

When the DBR reflectivity $R \to 1$, the factor $(1-R)^{-1}$ (which is proportional to the quality factor Q of the Fabry–Pérot mode) grows with the number of periods N as $\exp(2N\kappa\Lambda)$, where κ is the imaginary part of the field wave vector in the stop band and $\Lambda = L_1 + L_2$ is the DBR period. In a single resonant microcavity (SRM), when only the pump frequency is tuned at resonance, the conversion efficiency is proportional to $\exp(4N\kappa_\omega\Lambda)$. For a DRM we have two different possibilities. In a phase-matched microcavity, η is proportional to the product $Q^2_\omega Q_{2\omega} \propto \exp[2N(2\kappa_\omega + \kappa_{2\omega})\Lambda]$, while in the case of anti-phase matching the efficiency is proportional to the ratio $Q^2_\omega / Q_{2\omega} \propto \exp[2N(2\kappa_\omega - \kappa_{2\omega})\Lambda)]$. It is important to emphasize that the quality factors of single and double resonant microcavities are generally different, therefore a phase-matched DRM is more efficient than a SRM when

$$2\kappa^{DRM}_\omega + \kappa^{DRM}_{2\omega} > 2\kappa^{SRM}_\omega. \tag{7}$$

This condition can be fulfilled at a finite angle of incidence by proper structure design, as shown in the following.

The following results refer to single and double resonant microcavities with a GaAs cavity layer and with DBRs constituted of alternate layers of $Al_{0.4}Ga_{0.6}As$ (layer 1) and Alox (oxidized AlAs, layer 2). The field components coupled by the $\chi^{(2)}$ tensor depend on the growth direction of the sample. We have considered two different orientations of the nonlinear GaAs layer: (111) [with plane of incidence $(1\bar{1}0)$] and (001) [with plane of incidence (010)]. In all calculations we take into account the refractive index dispersion of the materials.[12]

The design of a DRM structure is made for a pump wavelength $\lambda = 2$ μm. We optimize the thicknesses L_1, L_2 of the DBR layers in order to obtain first and second-order stop bands (or photonic gaps) of comparable size.[8] Moreover, we choose the cavity layer thickness in such a way that the defect modes are resonant with the pump and harmonic waves at a finite angle of incidence. The following parameters are obtained: $L_1 = 104.8$ nm, $L_2 = 408.9$ nm, $L_c = 675$ nm. Figure

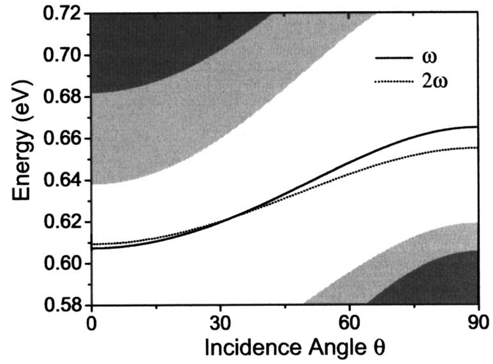

FIG. 2. Energies of p-polarized pump (solid line) and s-polarized SH defect modes in the stop bands (dotted line) as a function of the angle of incidence. The dark and light gray areas denote the regions outside the stop band for the pump and SH wave, respectively. Parameters are: $L_1 = 104.8$ nm, $L_2 = 408.9$ nm, $L_c = 675$ nm.

2 shows the angular dispersion of the defect modes at ω and 2ω, the latter being divided by two in order to visualize the double-resonance condition. The two defect modes are seen to cross at an angle of incidence around $\theta = 30°$.

We now calculate numerically the SH conversion efficiency by the nonlinear transfer matrix method.[13] The nonlinear transmittance T^{NL} normalized to that of an isolated cavity layer directly yields the cavity enhancement η. In Fig. 3 we compare the linear and nonlinear transmittance of SRM and DRM with (111) orientation. While in the first case the structure is designed to obtain only a pump resonance ($\lambda/4$ DBRs and no gap at 2ω), in the DRM all aspects of harmonic generation are optimized. In fact, in the DRM we have at the same time pump field confinement, good extraction efficiency of the SH, and phase matching between the two waves. Notice that the cavity modes at 2ω are shifted toward lower energies with respect to the pump by the material dispersion: double resonance for $p-s$ SH conversion is achieved by taking advantage of the polarization splitting.

The main idea of this method is to *compensate the dispersion of the cavity refractive index* n_c, *using the polarization splitting of the defect modes*. The splitting depends on the angle of incidence through the reflection phase shifts at the dielectric mirrors, and is especially large for DBRs with high refractive index contrast.[14,15] Experimentally, a further tuning parameter may be provided by sample inhomogene-

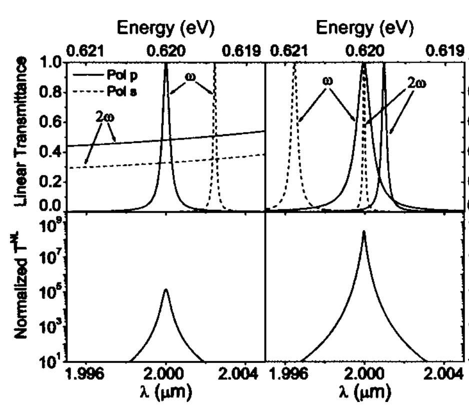

FIG. 3. Linear and nonlinear transmittance vs pump wavelength for a single-resonant (left) and doubly resonant microcavity (right) with $N = 6$ periods, at $\theta = 30°$. The SH calculation assumes a (111) orientation and $p-s$ conversion.

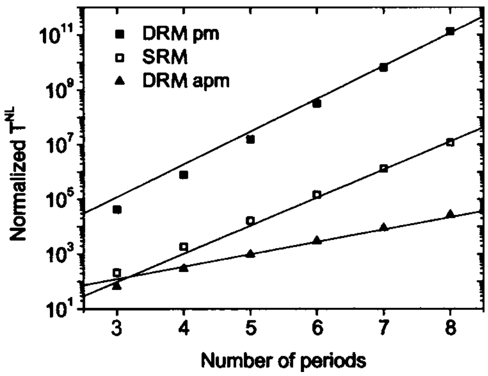

FIG. 4. Nonlinear transmittance as a function of N for double-resonant microcavities with both phase matching and anti-phase matching, and for single-resonant microcavities. The symbols denote the results of the transfer matrix calculation, while the lines represent the trends given by the Q factors.

ities, which yield a uniform variation of all thicknesses across the wafer.[7]

In Fig. 4 we present the normalized nonlinear transmittance for single and double resonant microcavities, as a function of the number of periods N in the DBRs. In all cases T^{NL} depends exponentially on N through the Q factors: $T^{NL} \propto Q_{\omega}^2 Q_{2\omega}$ for a DRM with phase matching, $T^{NL} \propto Q_{\omega}^2 / Q_{2\omega}$ for a DRM with anti-phase matching, $T^{NL} \propto Q_{\omega}^2$ for a SRM (lines). The DRM with phase matching is obtained with a (111) substrate orientation: indeed, choosing xz as the plane of incidence, the relevant nonlinear polarization is proportional to E_x^2 [i.e., $\alpha = \beta$ in Eq. (4)], and $\delta_m = 0$. In this case the cavity enhancement of SHG is larger than for a SRM since condition (7) is fulfilled. If we use instead the same structure, but with (001) orientation, the performance of DRM is strongly reduced by the anti-phase matching condition. In this case the SH depends on the product $E_x E_z$ (i.e., $\alpha \neq \beta$) and since $\phi_{x,\omega} = \phi_{z,\omega} + \pi$ we have $\delta_m = \pi$, so the resonance at 2ω determines destructive interference between the nonlinear polarization contributions. In this case the DRM is less efficient than a single resonant microcavity.

In the phase-matched case shown in Fig. 4, the exponential increase as a function of N is potentially much faster than with the band-edge resonance in periodic one-dimensional systems.[16,17] SHG enhancement in excess of 10^{10} can be achieved in phase-matched DRMs with a modest number of periods: with commonly used pulsed laser sources, this means that the conversion efficiency can grow up to a point where the SH intensity is a substantial fraction of the pump field intensity.

We have shown that double-resonance and phase-matching conditions can be fulfilled in GaAs microcavities with periodic AlGaAs/Alox dielectric mirrors by working at a finite angle of incidence and using the polarization splitting of the cavity modes to compensate the material dispersion. Under these conditions, the SH conversion efficiency grows exponentially with the number of DBR periods with the maximum slope. SH enhancement in excess of 10^{10} can be achieved with a device length $\sim 8\ \mu$m, meaning that an appreciable conversion efficiency can be attained with present-day pulsed laser source. Experimentally, the effect may be tuned by varying the angle of incidence and also by taking advantage of thickness variations in the wafer. Further work will consider other microcavity structures (e.g., with GaAs/AlGaAs DBRs) and effects beyond the nondepletion approximation.

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[1]N. Bloembergen and A. J. Sievers, Appl. Phys. Lett. **17**, 483 (1970).
[2]J. P. van der Ziel and M. Ilegems, Appl. Phys. Lett. **28**, 437 (1976).
[3]J. P. van der Ziel, Appl. Phys. Lett. **26**, 60 (1975).
[4]A. Fiore, V. Berger, E. Rosencher, P. Bravetti, and J. Nagle, Nature (London) **391**, 463 (1998).
[5]A. Ashkin and G. D. Boyd, IEEE J. Quantum Electron. **QE-2**, 109 (1966).
[6]Z. Y. Ou and H. J. Kimble, Opt. Lett. **18**, 1053 (1993).
[7]R. P. Stanley, R. Houdré, U. Oesterle, M. Gailhanou, and M. Ilegems, Appl. Phys. Lett. **65**, 1883 (1994).
[8]V. Berger, J. Opt. Soc. Am. B **14**, 1351 (1997).
[9]C. Simonneau, J. P. Debray, J. C. Harmand, P. Vidaković, D. J. Lovering, and J. A. Levenson, Opt. Lett. **22**, 1775 (1997).
[10]B. Shi and X. Wang, Appl. Phys. Lett. **80**, 3667 (2002).
[11]Notice that in expression (2) for δ_w any of the two Cartesian components for p-polarization can be used, since the corresponding phases $\phi_{i,w}$ differ by multiples of π.
[12]*Handbook of Optical Constants of Solids II*, edited by E. D. Palik (Academic, Orlando, 1991).
[13]D. S. Bethune, J. Opt. Soc. Am. B **6**, 910 (1989).
[14]G. Panzarini, L. C. Andreani, A. Armitage, D. Baxter, M. S. Skolnick, V. N. Astratov, J. S. Roberts, A. V. Kavokin, M. A. Vladimirova, and M. A. Kaliteevski, Phys. Rev. B **59**, 5082 (1999).
[15]A. A. Dukin, N. A. Feoktistov, V. G. Golubev, A. V. Medvedev, A. B. Pevtsov, and A. V. Sel'kin, Phys. Rev. E **67**, 046602 (2003).
[16]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).
[17]Y. Dumeige, I. Sagnes, P. Monnier, P. Vidakovic, I. Abram, C. Mériadec, and A. Levenson, Phys. Rev. Lett. **89**, 043901 (2002).