Noncollinear type-II second-harmonic generation in a Al(0.3)Ga(0.7)As/Al2O3 one-dimensional photonic crystal

Citation for published version (APA):
Bosco, A., Centini, M., Sciscione, L., Sibilia, C., Fazio, E., Bertolotti, M., ... Scalora, M. (2004). Noncollinear type-II second-harmonic generation in a Al(0.3)Ga(0.7)As/Al2O3 one-dimensional photonic crystal. Applied Physics Letters, 84(16), 3010-3012. DOI: 10.1063/1.1713039

DOI:
10.1063/1.1713039

Document status and date:
Published: 01/01/2004

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 31. May. 2019
Noncollinear type-II second-harmonic generation in a Al$_{(0.3)}$Ga$_{(0.7)}$As/Al$_2$O$_3$ one-dimensional photonic crystal

A. Bosco, M. Centini, L. Sciscione, C. Sibilia, E. Fazio, and M. Bertolotti

Istituto Nazionale di Fisica della Materia, INFM, at Dipartimento di Energetica—Università di Roma “La Sapienza,” Via A. Scarpa 16, I-00161 Roma, Italy

A. Fiore

Institute of Quantum Electronics and Photonics—Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland and Institute of Photonics and Nanotechnology, CNR, via dei Cineto Romano 42, 00156 Roma, Italy

A. Convertino and L. Cerri

Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via Salaria Km. 29.300, 00016 Roma, Italy

M. Scalora

Weapons Sciences Directorate, AMSRDI-RD-WS-ST, RD&EC, U.S. Army Missile Command, Building 7804, Redstone Arsenal, Alabama 35898-5000

(Received 27 October 2003; accepted 26 February 2004)

We demonstrate noncollinear type-II second-harmonic generation in one-dimensional photonic crystals. A 15-period Al$_{(0.3)}$Ga$_{(0.7)}$As/Al$_2$O$_3$ structure, 3.5 $\mu$m long, was designed, fabricated, and experimentally characterized. We measured an effective nonlinearity of (52±12) pm/V in perfect phase-matching conditions. © 2004 American Institute of Physics.

Recently, interest in second-order nonlinear optical phenomena occurring in periodic structures has grown considerably. These structures, usually referred to as photonic band gap (PBG) structures, may exhibit efficient parametric processes, such as second-harmonic generation (SHG) or frequency up- and down-conversion. In particular, during the last decade finite one-dimensional (1D), periodic or quasi-periodic multilayer stacks, the simplest types of PBG structures, have been widely investigated theoretically and experimentally. The main advantage that these artificial structures offer is the ability to enhance the nonlinear response normally associated with bulk $\chi^{(2)}$ materials thanks to the localization of light at frequencies tuned at the photonic band edge, and the simultaneous availability of effective phase matching (PM) conditions. In fact, the natural dispersion of ordinary materials can be compensated by introducing geometrical dispersion, which is brought about and controlled by properly juxtaposing a high and a low index material. This effect may provide enough anomalous dispersion across the photonic band gap to make exact PM conditions possible even for materials, such as III–V semiconductors, which cannot usually be phase-matched.

In this letter we present experimental evidence of phase-matched, noncollinear, type-II SHG in a photonic crystal. We used a 1D structure composed of 15 Al$_{(0.3)}$Ga$_{(0.7)}$As/Al$_2$O$_3$ periods. The structure was designed according to a theoretical representation of the effective index of refraction for a multilayer structure, such that multiple scattering events are taken into account to all orders, and the result is a bulk medium with an effective index of refraction $n_{\text{eff}}$. Using this approach, PM conditions can be found by applying the effective momentum conservation law in 1D structures $k_{\text{eff}}^{(2)} = k_{\text{eff}}^{(2)} - k_{\text{eff}}^{(s)} = 0$ and projecting it onto two components, one along the plane of the layers, and the other one perpendicular to it:

$$2n_{\text{eff}}^{(2)}(\omega, p) - n_{\text{eff}}^{(s)}(\omega, p) = 0, \quad (1a)$$

$$2\sin(\theta_{2\omega, p}) - \sin(\theta_{\omega, s}) = 0, \quad (1b)$$

where $\theta$ corresponds to the external incidence angle formed by each $k$ vector with the normal to the sample’s surface; the labels $p$, $s$, $\omega$, and $2\omega$ refer to the fields’ polarizations and frequencies. For a finite periodic structure, Eq. (1a) is automatically satisfied when the two fundamental fields are tuned at the band edge resonance, and the SH is tuned at the second peak near the second-order band gap. Equation (1b) depends only on the incidence angles of the fields, as if the $k$-vector components did not feel the refractive index discontinuity.

According to Eq. (1), exact, noncollinear PM for SHG of 1510 nm fundamental wavelength was found for a 15-period structure composed of Al$_{(0.3)}$Ga$_{(0.7)}$As (160 nm)/Al$_2$O$_3$ (97 nm). Total sample thickness was 3.5 $\mu$m. A multilayer structure of AlGaAs/AlAs was first grown on a 500-$\mu$m-thick (100) GaAs substrate by solid-source molecular beam epitaxy. A 30 nm GaAs cap was grown on the top of the multilayer to protect the surface from subsequent oxidation. Successively, 20-$\mu$m-wide trenches were etched through the entire multilayer by reactive-ion etching in order to expose the AlAs layers for lateral oxidation. The AlAs layers were oxidized by heating the sample at 410°C for 105 min in a H$_2$O atmosphere created by bubbling N$_2$ in a water bath at 85°C. The schematic layout of the multilayer structure and the real picture of the sample’s top surface are shown in Fig. 1(a); its active area is formed by 100 $\mu$m broad stripes separated by 20 $\mu$m etched trenches.

A spectral analysis of the structure was performed with a micro-reflectometer connected to a Fourier-transform ana-
MHz bandwidth. Several stripes. Figure 1 the sample homogeneity by comparing different spectra from to fit a single active stripe, a procedure that allowed checking ~Si detector.

FIG. 2. Layout of the experimental setup. The SH signal was detected by a Si detector (response time about 2 ns) connected to an oscilloscope with 500 MHz bandwidth.

The experimental SHG was obtained using the setup shown in Fig. 2. The laser system consisted of an amplified Ti:sapphire laser that pumped a parametric amplifier. The outgoing beam provided 2-ps-long pulses at 1 kHz repetition rate, with energy of about 25 μJ. A wave-plate rotated the polarization to obtain, after the polarizing beam splitter, two cross-polarized beams whose intensities were controlled by the variable attenuator. Both beams were focused on the sample by the same lens (focal length 500 mm) down to 180-μm-wide spot sizes. The two cross-polarized beams were sent to the sample with a relative angle of 27°. Their energies were varied up to a maximum of 4.5 μJ for each beam, corresponding to a peak intensity of approximately 9 GW/cm². In our conditions, the PBG acts like a resonant cavity; thus the SH is generated in both forward and backward directions. According to our theoretical model, the conversion efficiency \( \eta = I_{\text{SH}} / I_{\text{pump}} \) in nondepleted pump regime can be written as

\[
\eta^{(+,-)} = \frac{8 \pi^2 |d_{\text{eff}}^{(+,-)}|^2 L I_{\text{pump}}}{\varepsilon_0 c \lambda^2 n^{(2)(p,p)} n^{(2)(s,s)} n^{(2)(2s,p)}}
\]

where \( \lambda \) is the pump wavelength in vacuum, \((+,-)\) stand for forward and backward directions, and \(d_{\text{eff}}^{(+,-)}\) is the effective coupling coefficient containing the information on the fields overlap inside the structure, as described in Ref. 11. We note that Eq. (2) is formally equivalent to the equation that describes a phase-matched bulk medium, where the refractive index and the nonlinear coupling coefficient are replaced by effective quantities. Experimentally we were able to measure only the reflected SH because of the strong absorption present in the GaAs substrate at the SH wavelength. Figure 3 shows the measured reflected SH peak power versus the fundamental beam power. The experimental points are well fitted by a second-order polynomial function; this means that the process followed the theory of SHG in the nondepleted pump approximation. The measured conversion efficiency corresponding to the maximum fundamental beam intensity was \( \eta_{\text{PBG}} = (5.6 \pm 0.1) \times 10^{-7} \). The effective nonlinearity shown by the sample was then calculated by comparing this result with the one obtained by a reference nonlinear crystal, operating in transmission, under the same conditions of incident angles and fundamental beam intensity. For this calibration we used a crystal known in the literature with the acronym DAST. The crystal was 1.5 mm long, with...
Since the structure is embedded in air, there is a limit on the photonic-crystal modes that can be excited from outside. The dashed line sets the maximum value for the \( k_y \) component corresponding to a 90° external angle. PM conditions are almost fulfilled for any angle above the gap region. The presence of two peaks in the experimental angular emission is related to enhancement effects that are typical of structure of finite length. The main peak is obtained when the overlap between the two pump fields is maximized and perfect PM is achieved (30°). The second peak at 28° corresponds to band edge tuning for the SH. The strong SH field localization maintains the efficiency of the process, although the pump fields are slightly off resonance.

In conclusion, perfect PM conditions were achieved by using a material (Al\(_{0.3}\)Ga\(_{0.7}\)As) that cannot naturally be phase-matched because of its optical isotropy. We have provided experimental evidence of a relatively efficient, noncollinear, type-II SHG in one-dimensional photonic crystal 3.5 \( \mu \)m thick, i.e., more than twice the coherence length of bulk Al\(_{0.3}\)Ga\(_{0.7}\)As (approximately 1.5 \( \mu \)m). The structure showed an effective nonlinearity \( d_{\text{eff}}^{\text{PBG}} = (52 \pm 12) \) pm/V.

The authors kindly acknowledge L. Andreani and M. Galli for measurements of the linear spectra. This work was performed in conjunction with the FemtoLab INFM network.

\[ d_{\text{eff}}^{\text{PBG}} = (52 \pm 12) \text{ pm/V} \]