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Short Communication

Optical field enhanced nonlinear absorption and optical limiting properties of 1-D dielectric photonic crystal with ZnO defect

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ABSTRACT

We report on optical field enhanced nonlinear absorption and on the optical limiting properties of a 1-D photonic crystal with ZnO defect, fabricated by rf sputtering technique. The structural properties of the photonic crystal are studied using scanning electron microscopy (SEM) images. Light transmission spectroscopy measurement shows a broad photonic band gap with a defect mode. Open aperture Z-scan measurement with 532 nm pulsed laser illustrates a four times enhancement in the nonlinear absorption coefficient, due to local field enhanced two-photon absorption in the photonic crystal structure with respect to the single layer of ZnO reference. The enhancement of the nonlinear absorption in the photonic crystal, due to the strong confinement of the optical field around ZnO defect layer, leads to an optical power limiting behavior in the photonic crystal. The limiting threshold of the photonic crystal is found to be 0.74 J/cm^2 @ 532 nm with 6 ns pulse width, 10 Hz repetition rate.

1. Introduction

Photonic crystals are periodic optical structures at the nanoscale, which are able to control and manipulate the light in the same way semiconductors control the electrons [1] leading to many applications in the field of photonics and optoelectronics such as photonic crystal lasers, waveguides, optical switches and so on [2–5]. When a defect layer is inserted at the center of the photonic crystal structure, a localized optical mode appears in the photonic band gap (PBG) as a defect level and light can be strongly confined within the defect layer of the PBG [6]. The localization of the light leads to an increase in the optical electric field in the defect layer. If the nonlinear material is used as a defect medium, large enhancement of the nonlinearity are expected [7,8]. We have exploited this features to study the optical limiting behavior of 1-D dielectric photonic crystals activated by ZnO defect. ZnO is a largely employed semiconductor with a room temperature wide direct band gap of 3.37 eV [9].

The optical limiting phenomenon can be achieved by one or more nonlinear optical mechanisms such as two-photon absorption (TPA), free carrier absorption, self-focusing or defocusing and nonlinear scattering [10–12]. Scalora et al. first proposed one-dimensional single Bragg PBG optical limiter based on a nonlinear shift of the band edge [13]. Optical limiting in two-dimensional photonic crystals was proposed and experimentally examined using a thermal nonlinearity [14]. Recently, experimental results on optical limiting using photonic band edge effects, were reported in 1-D metallo-dielectric photonic crystals [15], semiconductor nanocrystals embedded in photonic bandgap structures [16] and also in 3-D colloidal photonic crystals [17]. Liu et al. theoretically studied the optical limiting properties of one-dimensional photonic crystals with respect to thick bulk materials

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and it was found that the optical limiting ability of the composite structure is improved by two orders of magnitude with respect to the bulk material [18]. Till now, the experimental evidence of optical limiting properties in 1-D photonic crystals has not been reported. In this paper, we report on optical limiting behavior in 1-D photonic crystal fabricated by RF sputtering, constituted by two SiO_2/TiO_2 Bragg mirrors and a ZnO defect layer.

2. Experimental section

The 1-D photonic crystal with ZnO defect is composed of 21 alternating layers of high and low refractive indices of TiO_2 and SiO_2, respectively, with an optical thickness of $\lambda/4$ ($\lambda = 549$ nm). 1-D photonic crystal with ZnO defect was prepared by multi target sputtering technique using silicon and silica substrates. The samples deposited on silica substrate were used to measure the linear and nonlinear optical properties, while the ones deposited on silicon were employed for SEM analysis. The substrates were cleaned inside the rf sputtering deposition chamber by heating at 120 °C for 30$'$ just before the deposition procedure. More details about the fabrication of 1-D photonic crystals by multi target sputtering can be found here [6,19]. Sputtering deposition of the Bragg reflectors was performed by sputtering alternatively a 15×5 cm^2 titania and a 15×5 cm^2 silica targets, a 15×5 cm^2 ZnO target was used for the defect layer. The residual pressure, before the deposition, was about 8.5×10^{-7} mbar. The sputtering occurred with an Ar gas pressure of 5.4×10^{-3} mbar; the applied rf power was 150 W and 130 W for silica and titania targets, respectively. The applied rf power was 90 W for ZnO target. The deposition time necessary to reach the appropriate thickness of the Bragg mirror layers were 50 min and 30 min for titania and silica targets, respectively. The deposition time necessary to reach the appropriate thickness of the ZnO defect layer, to obtain cavity resonance centered at 549.2 nm, was 36 min.

The surface morphology of the multilayer films and the thickness of each layer were obtained using field enhanced scanning electron microscopy (FESEM). M-line spectroscopy was employed to obtain the refractive index and thickness of single layers of SiO_2, TiO_2, and ZnO films.

The transmission spectrum of 1-D photonic crystal with ZnO defect and linear absorption spectrum of ZnO reference sample were measured using UV–Vis double-beam spectrophotometer with a resolution of 0.1 nm. Angle resolved reflectance studies were carried out with variable angle reflectance set up, which is attached to the spectrophotometer.

The nonlinear optical absorption and optical limiting studies of 1-D photonic crystal with ZnO defect and ZnO reference were investigated using Z-scan technique [20] with ns laser pulses. The ns laser is a frequency doubled, Q-switched Nd: YAG laser, delivering 6 ns pulses at 532 nm with a repetition rate of 10 Hz. The well-established Z-scan technique, which consists of a focussed single beam method and the translation of the sample across the focal point, was used for measuring nonlinear absorption of the samples [20]. A lens with focal length of 12 cm was used to focus the Gaussian beam and the sample moved through the beam waist of the laser beam over the length of 60 mm. The transmitted light was collected with a large- area fast silicon photodiode. To allow a direct comparison, the nonlinear absorption was measured for the photonic crystal and for the single layer of ZnO. The ZnO layer, used as reference, was deposited on a SiO_2 substrate during the same deposition run in which the photonic crystal was fabricated. The reference was therefore obtained employing the same fabrication protocol and target used for the photonic crystal so that the defect layer in the 1-D photonic crystal and the reference sample have the same thickness and composition.

3. Results and discussions

The microcavity is constituted by ZnO half wave layer inserted between two Bragg reflectors each one consisting of 21 alternating SiO_2/TiO_2 quarter wave layers. Fig. 1(a) represents the SEM micrograph of the cross section of the 1-D photonic crystal with ZnO defect. The dark and bright regions correspond to SiO_2 and TiO_2 layers, respectively. The thick bright line between the two Bragg reflectors corresponds to the ZnO defect layer. From the SEM image, we estimated thicknesses of the silica and titania layers as 100 ± 5 and 50 ± 5 nm, respectively. ZnO defect layer thickness is found to be 160 ± 5 nm. The refractive indices at 633 nm of silica, titania, and ZnO layers, measured by m-line spectroscopy on the single layer films, are 1.457 ± 0.002, 2.35 ± 0.02, and 2.01 ± 0.02, respectively. The thickness of the single layer films, measured by m-line spectroscopy, is in good agreement with the values obtained from SEM analysis. The visible region transmission spectrum, measured at zero degree of incident angle, is shown in Fig. 1 (b). The stop band ranges from 435 nm to 580 nm. The narrow peak in the transmittance spectrum at 549.2 nm corresponds to the cavity resonance wavelength. The transmittance spectrum presented in the inset of Fig. 1(b), obtained with a resolution of 0.1 nm, evidences the sharp resonance line.

Angle resolved reflectance spectra of 1-D photonic crystal with ZnO defect measured at 3° and 30° is shown in Fig. 2(a). The

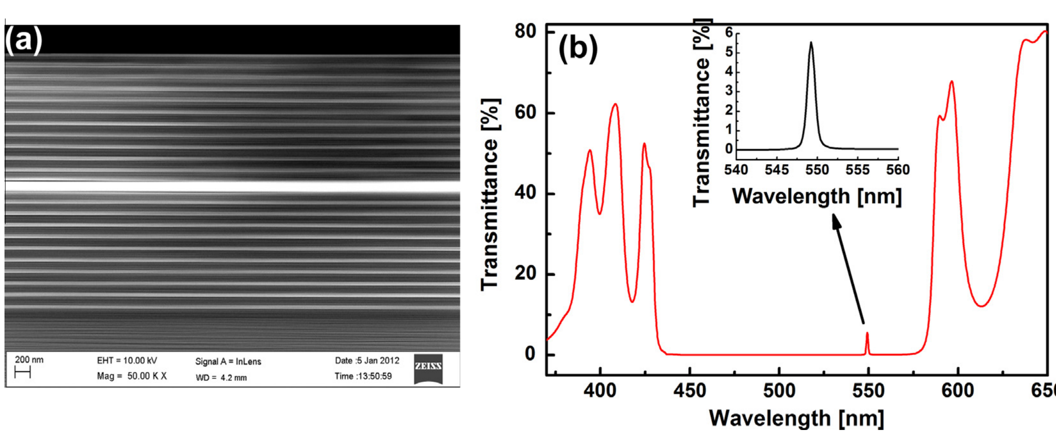

Fig. 1. (a) SEM micrograph of the 1-D microcavity cross section. The bright and the dark regions are TiO_2 and SiO_2 layers, respectively; the ZnO defect layer can be recognized at the center. The substrate is located at the bottom of the image and the air on the top. (b) Transmittance spectrum of the cavity with 21 pairs TiO_2 and SiO_2 layers Bragg mirrors. Inset graph is transmission spectrum of the cavity resonance correspond to the sharp maximum at 549.2 nm. The incident light is unpolarized.