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Sreekanth Kandammathe Valiyaveedu

Nanyang Technological University

Alireza R. Rashed

Case Western Reserve University

Alessandro Veltri

Universidad San Francisco de Quito (USFQ)

Mohamed Elkabbash

The University of Arizona

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Optical bistability in Ag-Al_2O_3 one-dimensional photonic crystals

Kandammathe Valiyaveedu Sreekanth[1(a)], Alireza R. Rashed[1], Alessandro Veltri[2], Mohamed ElKabbash[1] and Giuseppe Strangi[1,3(b)]

[1] *Department of Physics, Case Western Reserve University - 10600 Euclid Avenue, Cleveland, OH 44106-7079, USA*
[2] *Colegio de Ciencias e Ingeniería, Universidad San Francisco de Quito - Quito 17-1200-841, Ecuador*
[3] *Department of Physics and CNR-NANOTEC, University of Calabria - 87036, Rende, Italy*

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Abstract – Here, we demonstrate the nonlinear optical responses of Ag-Al_2O_3 one-dimensional photonic crystals (1D PCs). The linear transmission spectra of the proposed 1D PC show higher transmission at shorter wavelengths and lower transmission at longer wavelengths with "N" pairs of Ag-Al_2O_3 will support "$N - 1$" transmission peaks. By using 5 pairs of Ag-Al_2O_3, the optical bistability behavior of light transmission at low input intensity for the resonant modes is numerically demonstrated. Then, we performed a Z-scan experimental technique to show the enhanced nonlinear optical transmission of Ag-Al_2O_3 1D PC. These results can pave the way for achieving all-optical control of light for potential applications such as all-optical switching, optical logic, optical computation, etc.

In recent years, metal-dielectric photonic crystals (MD-PCs) have received considerable attention in the field of nanoscience, nanotechnology, and plasmonics due to their high optical transparency and low electrical sheet resistance [1–3]. Interestingly, the photonic band gap of MD-PCs is higher than that of dielectric-dielectric photonic crystals (DD-PCs) due to their large reflectivity at the metal-dielectric interfaces [4]. Due to the high reflective properties of metals below the plasma frequency, the electromagnetic field is highly confined inside the dielectric layers of the MD-PCs. In addition, MD-PCs show very high transmission values due to their resonant tunneling mechanism. The linear transmission properties of 1D MD-PCs have been reported by many groups, which show that the overall transmittance in the pass band depends on the number of periods in the PC structure [4–7]. In addition, the nonlinear optical response of 1D MD-PCs has been studied both experimentally and theoretically [8–11]. Recently, Lepeshkin *et al.* has experimentally demonstrated the strongly enhanced nonlinear optical response in transmission using Cu/SiO_2 PCs [11]. The strong field localization effect in 1D MD-PCs has also been demonstrated [12,13]. These results suggest that enhanced transmission and high field localization is possible from 1D MD-PCs. Since optical bistability requires strong optical nonlinearity, 1D MD-PCs would be an alternative choice for the realization of optical bistability devices.

Optical bistability is a nonlinear phenomenon in which the transmission properties of light changes with respect to the nonlinear optical response of the system, which can find potential applications in all-optical information systems [14]. Specifically, two stable resonant transmission states are available in such devices, depending on the input power. In the recent past, the nonlinear photonic crystals have been extensively considered for the study of optical bistability [15–18], whereas an enhanced nonlinear effect is achieved by field localization and the field enhancement effect at the point defects of the PCs. However, the main drawback of the optical bistability devices based on nonlinear PCs reported so far is to achieve a sizeable nonlinear response at low threshold intensity using their minimum size. Recently, MD-PCs have been considered as potential nonlinear optical materials due to the extremely large nonlinear optical response of metals. It has been theoretically and numerically demonstrated by many authors that 1D MD-PC is a possible nonlinear optical material for realizing optical bistability devices at low threshold input intensities [12,13,19–21]. Furthermore, the optical bistability effect in a subwavelength metal-dielectric

(a) E-mail: sxk923@case.edu
(b) E-mail: giuseppe.strangi@case.edu

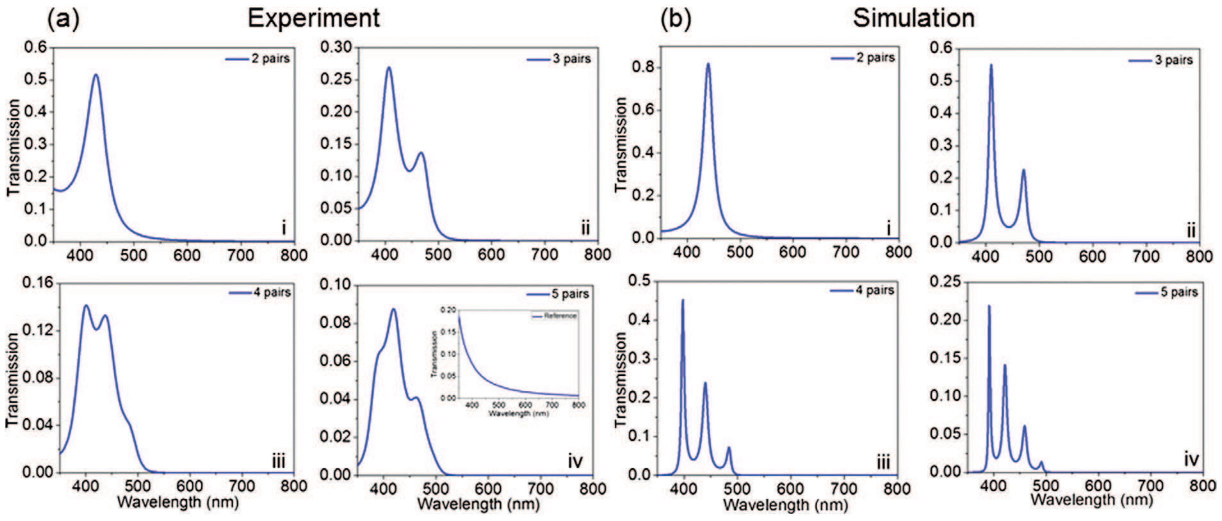

Fig. 1: (Colour on-line) Transmission spectrum of 2 to 5 pairs of Ag-Al_2O_3 at normal incidence: (a) experiment and (b) simulation. The transmission spectrum of the reference sample is shown in the inset of panel (a-iv).

multilayered metamaterial has been numerically investigated [22] and the enhancement of optical nonlinearity in metal-dielectric stacks at infrared frequencies was experimentally realized [23]. In this work, we demonstrate the optical bistability phenomena in 1D Ag-Al_2O_3 photonic crystal at visible frequencies. First, we show the linear transmission properties of designed 1D Ag-Al_2O_3 PCs. Then a Z-scan experimental technique will be used to show the enhanced nonlinear optical response of the proposed geometry.

The proposed 1D photonic crystal consists of alternating layers of Al_2O_3 and Ag thin films. The designed structure was realized by the sequential deposition of Al_2O_3 and Ag on a glass substrate using electron beam evaporation and thermal evaporation techniques, respectively. The deposition rate of Al_2O_3 and Ag was set to be 0.5 A/s and 0.3 A/s, respectively. Spectroscopic ellipsometry (V-VASE, J.A. Woollam Co., Inc,) measurements have been carried out to estimate the thicknesses of grown thin films. The estimated thickness of Al_2O_3 and Ag are 101 nm and 30 nm, respectively. Silver has been selected as the metal due to its relatively low loss and extremely high nonlinear susceptibility in films as compared to other metals with higher nonlinear susceptibility. In order to obtain higher transmission as well as large field localization for optical bistability, the optimal thickness of Ag was set to 30 nm. The transmission and reflection measurements were performed using J.A. Woollam Co. Inc V-VASE variable-angle spectroscopic ellipsometer. The transmission measurements were performed at normal incidence, whereas reflection measurements are performed at oblique incidence. In all our experiments and simulations, the polarization of the beam was considered as transverse electric (TE) to avoid the plasmonic resonance excitation.

The linear transmission measurements of Ag-Al_2O_3 multilayers with different number of pairs (2 to 5 pairs) are shown in fig. 1(a). From fig. 1(a), it is clear that 1D PC shows higher transmission at shorter wavelengths and lower transmission at longer wavelengths, providing "$N-1$" transmission peaks with "N" number of bi-layers. The number of transmission peaks represents the number of resonant modes of a coupled nanocavity: in fact a thin dielectric film sandwiched by two metallic reflecting layers can be considered as a Fabry-Pérot (FP) resonant nanocavity [12]. Note that the light transmission decreases as the number of pairs is increased from 2 to 5 due to the Ag absorption. In addition, the fourth resonant mode of 5 pairs is not visible at higher wavelengths because of the higher absorption loss of Ag at higher wavelengths. Nonetheless, reflection measurements give the full information about the resonant modes of coupled nanocavity. The reflection spectra of 2 to 5 pairs of Ag-Al_2O_3 at 15° incident angle are shown in fig. 2(a). It is evident that the resonant reflection dips are slightly blue shifted from the positions of the resonant transmission peaks due to oblique incidence. For the case of 5 pairs, the fourth mode is clearly visible at higher wavelengths (around 497 nm), which was absent in transmission measurements. These results show that the overall transmittance in the pass band depends on the number of periods of the PC structure.

A transfer matrix method (TMM) [24] has been used to numerically simulate the transmission and reflection spectra. In our simulation, the relative permittivity of Ag is described by the Drude model, $\varepsilon_{Ag}(\omega) = \left(\varepsilon_\infty - \left(\omega_p^2/\left(\omega^2 + i\nu\omega\right)\right)\right)$, with $\varepsilon_\infty = 5$, $\omega_p = 5\,\text{eV}$ and $\nu = 0.105\,\text{eV}$ [12]. The dielectric constant of Al_2O_3 was obtained from the ref. [25]. The simulated transmission and reflection spectra of 2 to 5 pairs of Ag-Al_2O_3 are shown in fig. 1(b) and fig. 2(b), respectively. They show that the numerically obtained results (spectral positions of transmission peaks and reflection dips) are well correlated with experimental data.

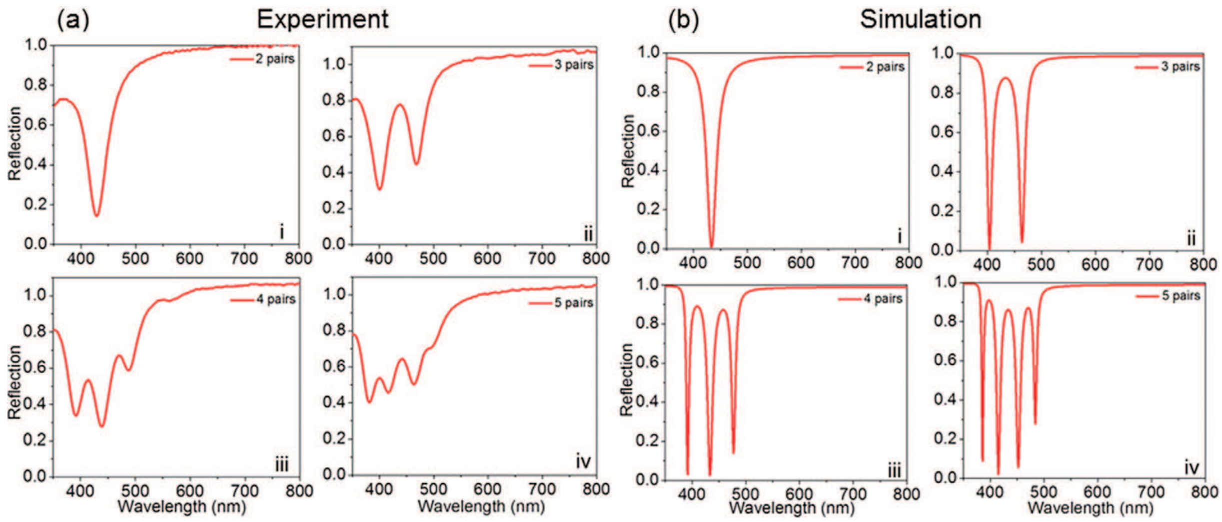

Fig. 2: (Colour on-line) Reflection spectrum of 2 to 5 pairs of Ag-Al_2O_3 at 15° angle of incidence: (a) experiment and (b) simulation.

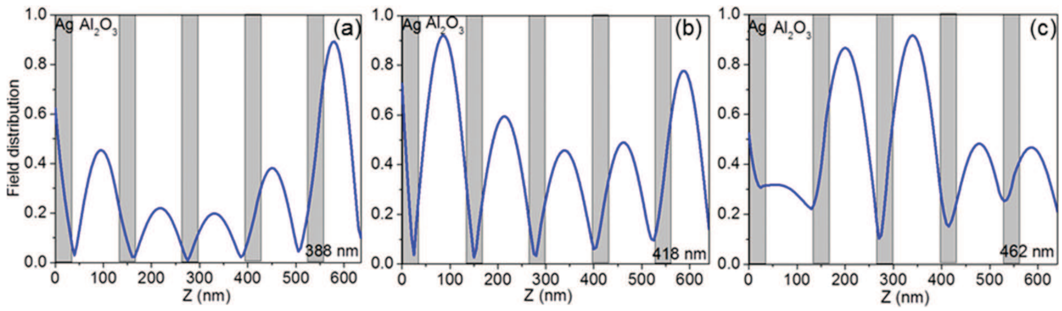

Fig. 3: (Colour on-line) Simulated field amplitude distribution inside the 5 pairs of Ag-Al_2O_3 for the first resonant mode ($\lambda = 388$ nm) (a), for the second resonant mode ($\lambda = 418$ nm) (b) and for the third resonant mode ($\lambda = 462$ nm) (c).

We now consider 5 pairs of Ag-Al_2O_3 as a 1D metal-dielectric photonic crystal for optical bistability study. At first, we study the field localization effect in 5 pairs of Ag-Al_2O_3 for the resonant modes (at 388 nm, 418 nm and 462 nm). The field distribution study gives the information about how the resonant modes are generated in the 1D PC. A finite difference time domain (FDTD) method with periodic boundary conditions has been used to determine the field distribution in the structure. The field amplitude distribution along the 1D PC (z-axis) is shown in fig. 3. One can see that the electromagnetic field is largely localized in the nanocavity (dielectric layer) region of the structure for three resonant wavelengths. In the case of the first (388 nm) and third (462 nm) resonant modes, the field intensity is randomly varying throughout the structure. However, the field intensity is almost equally distributed along the structure for the second resonant mode (418 nm). The obtained results show that the strong field localization effect is possible for three resonant modes, which can be useful for the realization of optical bistability in 5 pairs of Ag-Al_2O_3.

In order to demonstrate the nonlinear optical response of 1D Ag-Al_2O_3 PC, first we numerically study the optical bistability phenomenon in 5 pairs of Ag-Al_2O_3. For this purpose, we used an approach of the effective-medium approximation [13]. Here, we considered a 1D metal-dielectric PC as a homogeneous slab of the material with nonlinear Kerr-like response $\varepsilon_{eff}^{NL} = \varepsilon_{eff}^{L} + \varepsilon_0 \langle \chi_3 \rangle E^2$. In the calculation, the cubic susceptibility (χ_3) of Ag has been taken as $2.49 \times 10^{-8} + i7.16 \times 10^{-9}$ esu [13] and the nonlinearity of Al_2O_3 was neglected. Since the optical bistability behavior is not obtainable when the incident wavelength is equal to resonant wavelength [12], the wavelength close to three resonant modes is used here to show the optical bistability phenomena in 1D Ag-Al_2O_3 PC. The dependence of the transmitted intensity on the incident intensity at 390, 420, and 465 nm wavelengths is shown in fig. 4(a), (b) and (c) respectively. This was calculated from the transmitted side to the incident side by solving the system of equations presented in [26] via a Runge-Kutta scheme of the fourth order. As shown in fig. 4, an optical bistability effect is observed for all incident wavelengths. Specifically, bistable behavior with two stable (first and third branch) and one unstable (second branch) states is possible for a certain range of input intensities. The optical bistability at the lowest threshold input

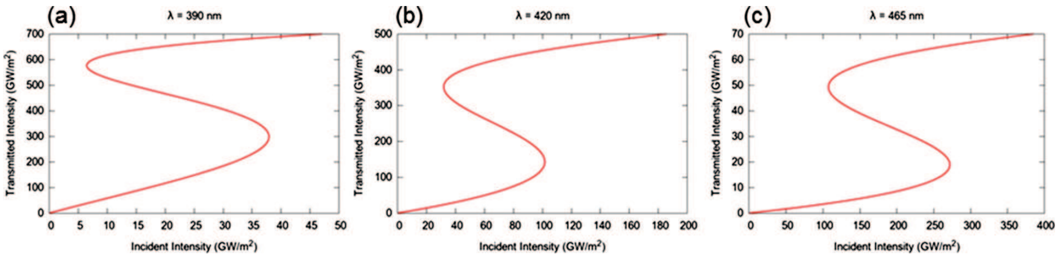

Fig. 4: (Colour on-line) Simulated transmission intensity dependence on input intensity for 5 pairs of Ag-Al_2O_3. (a) at $\lambda = 390\,\text{nm}$, (b) at $\lambda = 420\,\text{nm}$ and (c) at $\lambda = 465\,\text{nm}$.

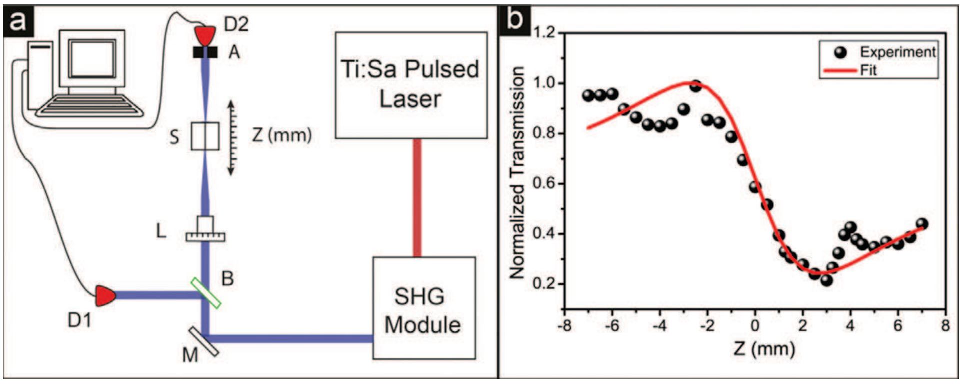

Fig. 5: (Colour on-line) (a) A schematic representation of a closed aperture Z-scan setup. SHG: second harmonic generator; M: mirror; B: beam splitter; L: 10× objective lens; S: sample; A: aperture; D1: power meter detector; D2: spectrometer detector. (b) Normalized transmission of 5 pairs of Ag-Al_2O_3. The solid line represents the theoretical fit to the data.

intensity is obtained for the first wavelength (390 nm), which is around $40\,\text{GW/m}^2$. This value is lower than the previously reported threshold incident intensity required for achieving optical bistability in Ag-SiO_2 1D PCs [12]. However, a higher threshold input intensity is required to realize optical bistability for other two wavelengths ($100\,\text{GW/m}^2$ for 420 nm and $280\,\text{GW/m}^2$ for 465 nm). The mechanism of bistable behavior here is that the nonlinear effects (ε_{eff}^{NL}) in the 1D PC increases due to the presence of an electric field and then the 1D PC becomes transparent due to the positive permittivity (*i.e.* 1D PC behaves as a dielectric medium) [13].

We performed a closed aperture Z-scan experiment [27] to demonstrate the nonlinear transmission of 1D MD PC made by 5 Ag-Al_2O_3 pairs. In order to compare the obtained results, we considered 62 nm thick Ag film on a glass substrate as a reference sample. According to the inset of fig. 1(a), the reference sample provides almost the same transmission values of 5 pairs of Ag-Al_2O_3 particularly at 400 nm wavelength. As shown in fig. 5(a), the sample (S) is placed on a single-axis translation stage that allows to vary the position of the sample with respect to the focal point of the 10× objective lens (L) along the z-axis and an aperture "A" was placed before the detector. The sample was irradiated with pulsed-laser wavelength of 400 nm from the substrate side. In order to obtain this wavelength, we used a Ti:Sapphire pulsed laser (by Coherent Inc.) with repetition rate = 80 MHz, pulse width = 140 fs, operating at 800 nm and a second harmonic generation (SHG) module. The incident laser power was measured by a Coherent-LabMax-top laser power meter equipped with highly sensitive thermal-type detector (D1). The calculated power density for an incident power of 200 mW is around $3\,\text{MW/m}^2$. The transmitted light was collected with a multimode fiber (D2) and sent to spectrometer in order to be spectroscopically analyzed by means of a CCD camera (by Andor). The transmission in the far field was measured by moving the sample through the focal point. Note that the measurements were repeated several times and average values were used to plot each data point in fig. 5(b). The closed aperture Z-scan result of Ag-Al_2O_3 1D PC is a peak-valley profile, which shows that 1D PC holds an effective nonlinear refractive index. However, no such profile was obtained in the case of the reference sample (not shown). In particular, fig. 5(b) represents the intensity-dependent fractional transmission changes, which depend on the complex effective refractive index of the material [27]. Here, the experimental data are fitted to [27], $T(z) = 1 + \frac{4\Delta\varphi x}{(x^2+9)(x^2+1)}$ with T the normalized transmission, $\Delta\varphi$ the on-axis phase change caused by the nonlinear refractive index of the 1D PC, and $x = z/z_R$ with $z_R = \pi\omega_0^2/\lambda$, where ω_0 is the beam waist radius of the focus and λ is the wavelength of the laser beam. $\Delta\varphi$ depends on the nonlinear refractive index, which, in turn, depends on the third-order nonlinear susceptibility [27]. Therefore, the obtained Z-scan result shows that enhanced nonlinear optical responses are possible for 1D MD PC as compared to the reference sample since the nonlinear susceptibility characterizes the intensity-dependent change in the dielectric function of the material [11].

In conclusion, a one-dimensional Ag-Al_2O_3 photonic crystal have been designed and fabricated to experimentally show the enhanced nonlinear optical response. First, the linear transmission properties of different pairs of Ag-Al_2O_3 have been investigated which showed that structures with "N" pairs of Ag-Al_2O_3 support "$N-1$" transmission peaks, as expected. The supporting numerical simulation results were also presented. Then, we numerically demonstrated the optical bistability effect at low threshold input intensities for the resonant modes using 5 pairs of Ag-Al_2O_3. The nonlinear optical responses of 1D PC were experimentally demonstrated using a Z-scan technique. The presented results can pave the way for achieving all-optical control of light for many potential applications.

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