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Investigation the Nonlinear Optical properties of Silver Nanoparticles Using Femtosecond Laser

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Abstract. In this research, the fabrication of silver nanoparticles and experimental nonlinear response (NLO). The fabrication of the silver nanoparticles has been done using E-Beam evaporation on a glass substrate (Ag-NPs) and investigation of their nonlinear optical response (NLO). The silver nanoparticles was evaluated by optical spectrum (UV-Vis) that shows localized surface Plasmon band at 375 nm. The experiment shows the nonlinear absorption and nonlinear refraction effect of silver nanoparticles, the silver nanoparticles is analysed by Z-Scan technique using a femtoseconds laser with 800 nm wavelength. The result shows the nonlinear absorption (NLA) is at $4.87 \times 10^{-4} \text{ cm}^2 \text{ W}^{-1}$, while (NLR) is at $7.94 \times 10^{-9} \text{ cm}^2 \text{ W}^{-1}$.

Keywords— : *Silver coating and silver nanoparticles;*

1. Introduction

The nonlinear optical defined as the branch of optics that study behaviour of the light in nonlinear medium which include the propagation of intense light beams in solids, liquids, and gases and their interaction with matter. The response of nanomaterial nonlinearity is used in many applications such as biosensors, photonic devices, and optical limiters. numerous studies have suggested that the surface



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of nanoparticles (NPs) plays a crucial role in determining linear and nonlinear optical properties. The structure of nanoparticles (NPs) shows interesting features in optical properties materials. The noble materials such as gold, silver and copper nanoparticle shows comprehensive absorption spectra in the visible light. The nonlinearity of Ag nanoparticle films have been investigated using Z-Scan technique [1], Au NPs colloids [2] and composite films of Ag fabricated using various methods [3] have been studied. The surface plasmon resonance of noble nanoparticles (NPs) show absorption peak in visible range with sharp peak. The nanoparticle with different distributions of various types, shapes, and substrates can be creating by several methods, thermal evaporation, sputtering technique laser ablation and E-beam lithography [1]. This research paper study randomly Ag nanoparticles (NPs) deposited on the soda-lime glass. In order to determine optical characteristics to a substantial degree Surface Plasmon Resonance (SPR) is determined. The effect of SPR peak is used to ultimately choose the best nanoparticles material. Furthermore, the chosen material affect the optical application and the overall performance for example light-switch, optical limiting, and surface-enhanced Raman scattering [4-8]. The nonlinear optical properties of Ag-NPs investigated using Z-Scan technique with femtosecond laser at 800 nm.

2. Setup of the Experiment

2.1. Preparation of the Sample

The sample preparation involve Ag metal being deposition on soda-lime glass substrate using E-Beam Evaporation. The thin and smooth layer of silver materials was first spread clean the substrate via this process. The thickness of the materials depend on deposition duration. The annealing temperature is set at 250°C and annealing duration of 2 hours. The annealing temperature for silver nanoparticle is much lower compared to other materials melting temperature of silver relative [1, 9-12]. The UV-Vis spectroscopy take place to identify the peak Absorption of silver nanoparticles. field-effect scanning electron microscope (FESEM) images is used to determine a 375nm absorption of Ag nanoparticles. Z-Scan under 800 nm excitation through femtosecond laser is used to investigate the optical nonlinear characteristics of the nanomaterial prepared.

2.2. Using of Z-Scan Technique in the experiment setup

Using Z-Scan in our experiment is important to determine the index of nonlinear refraction (NLR) and two-photon absorption (TPA) coefficient [13]. A femtosecond laser with 800 nm wavelength, at duration of 100 fs and a 82MHz repetition rate. An average power of 33mW and 0.15 nJ of energy used to study the nonlinear effect. The lens focuses used in the setup was at length of 75 mm with irradiated beam of 2.5 mm[14]. The linear phase shift focus used to express by the power series $\Delta\Phi_0(t)$ [15] see also [16, 17].

3. Results and discussions

3.1. UV-Vis Absorption

The nonlinear optics characteristics of Ag-NPs are shown localizes surface plasmon resonance (LSPR) effect in 375 nm. The UV-Vis spectra (recorded using Perkin Elmer) absorption of Ag-NPs shows in Figure 1.

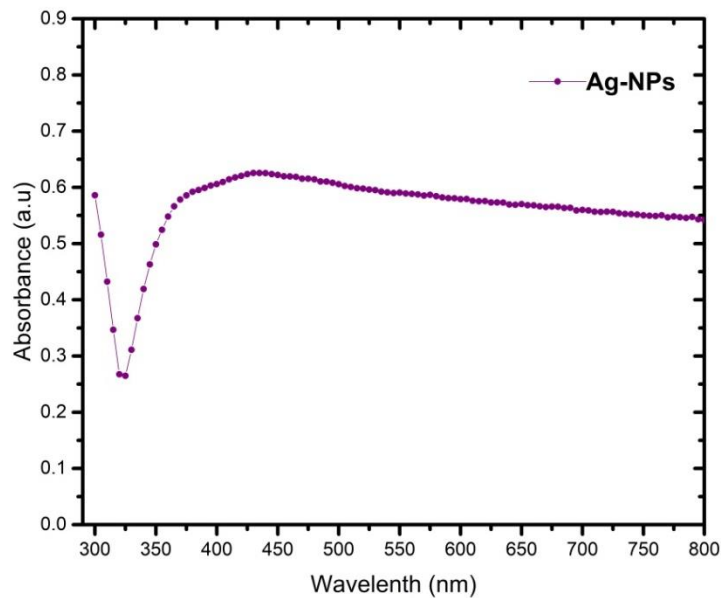


Figure 1. Absorption spectra of Ag-NPs

3.2. FESEM Images

FESEM analysis is used to determine the metallic nanoparticles morphology, size distribution and particle density. This analysis is important because of the particle size and density possibly determines the plasmonics behaviour of the nanoparticle layers. Observation obtained from SEM showed in Figure 2 that Ag films had different sizes of granular structures formed on top of the wafer from the annealing. The annealing temperature is set at 250°C and annealing duration of 2 hours enough to create nanoparticles. In this experiment, 250°C is the suitable temperature for Ag film because high temperature can cause the significant silver evaporation. At temperature of 250°C, agglomeration occurs where the Ag islands start to experience mass transfer between themselves. For film thickness of the deposition (~20 nm) the islands are well-separated and in round or oval shape. [9-11, 18].

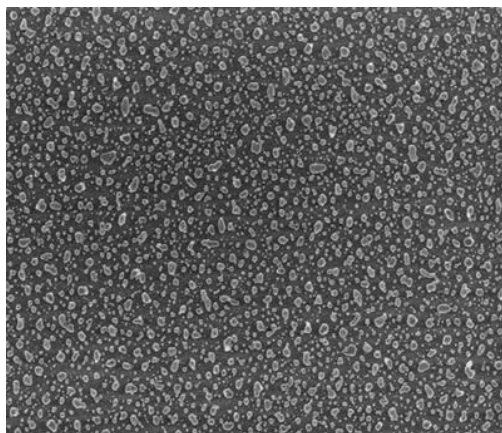


Figure 2. Image of Silver nanoparticles Ag-NPs samples have attributed to size distributions of metal nanoparticles.

3.3. Optical Properties

The magnitude of β (magnitude of nonlinear absorption) and the nonlinear refraction index (n_2). Both parameters affect the response of Ag-NPs films in terms of open and close aperture. In order to measure the aperture a transmission and normalization is performed. As shown in Figure 3.

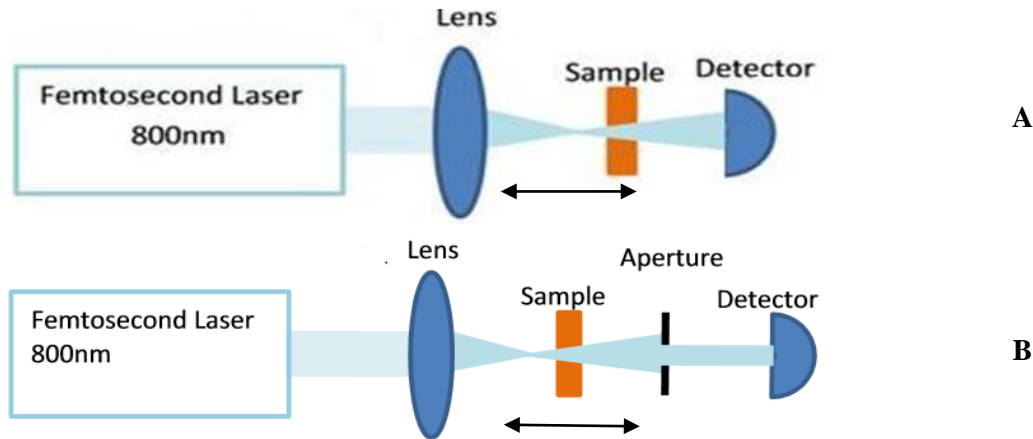


Figure 3. Schematic diagram of open & close aperture Z-Scan technique.

The linear absorption of silver nanoparticle invoke a comparison between the linear absorption for samples containing particles and the substrate without nanoparticles. Furthermore, a percentage of power transmitted through the particles containing sample (p), and percentage of transmitted power within the substrate material (p_0), the relation equation for linear absorption (α) is represented and calculated as shown in Equation. (1)

The Equation for linear absorption, α

$$\alpha = \frac{-1}{L} \ln\left(\frac{p}{p_0}\right) \quad (1)$$

where r_a is the radius of the aperture and w_a is the beam radius at the aperture.

where p is the power transmitted through a sample containing nanoparticle layer, and p_0 is the power transmitted through the substrate material without the nanoparticle layer. The sample thickness, L is determined by measuring the nanoparticle height using a surface profiler (DEKTAK D150). The linear absorption for the silver nanoparticles samples is tabulated in Table 1.

Another important parameter in the calculation of NLA and NLR coefficient is the effective thickness of the sample, L_{eff} . L_{eff} can be calculated from the linear absorption coefficient as shown in Equation (2). [19]:

$$l_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \quad (2)$$

For measurement of nonlinear optical interaction, the sample is translated along the laser beam propagation direction (Z-axis) where the laser focal point is set as $Z = 0$. In the open-aperture Z-Scan setup in Figure 3(a), the measured transmittance of the nanoparticle samples will be reduced as the sample is translated through the laser focal point due to NLA by the sample. The transmittance profiles of silver nanoparticle layers are shown in Figure 3(a). It can be seen that the open aperture transmittance is symmetric in relation to the focal point $Z = 0$. The NLA coefficient (β) can then be determined by measuring the peak-valley value, $\Delta T_{(z)}$ of the transmittance profile.

The NLA coefficient (β) is calculated using Equation (3):

$$\beta = \frac{2\sqrt{2}}{I_o L_{eff}} \Delta T(z) \quad (3)$$

The close-aperture Z-Scan setup in Figure 3(b). An aperture is inserted near the detector to cut out a portion of transmitted light incident upon the detector. For close-aperture Z-Scan setup, both NLA and NLR effects will be measured. The close-aperture Z-Scan transmittance profile is then analysed together with open-aperture Z-Scan transmittance profile to determine the NLR coefficient. In this case a second parameter is introduced which is the S parameter. It is the normalized transmittance parameter and is represented by Equation 4:

$$S = 1 - \exp\left(\frac{-2r_a^2}{w_a^2}\right) \quad (4)$$

Where r_a is the radius of the aperture and w_a is the beam radius at the aperture.

For open aperture Z-Scan measurement, S is equal to unity ($S=1$) since all transmitted light is measured by the detector. Whereas for close-aperture Z-Scan measurement, S parameter varies from 0.4 due to the requirement for S value to be between $0 \leq S \leq 0.5$.

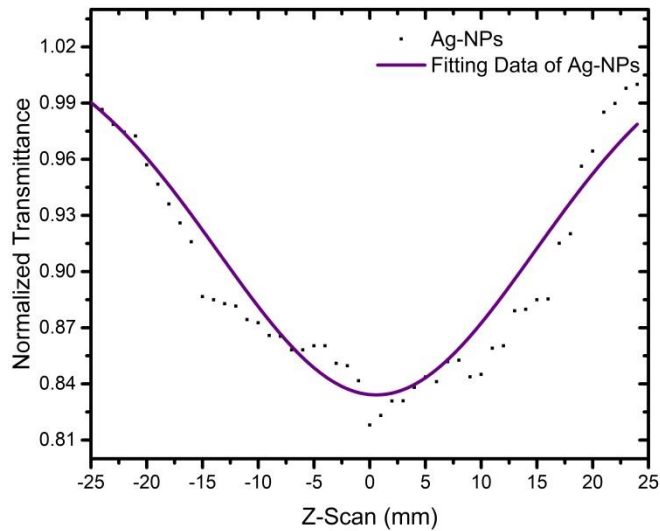
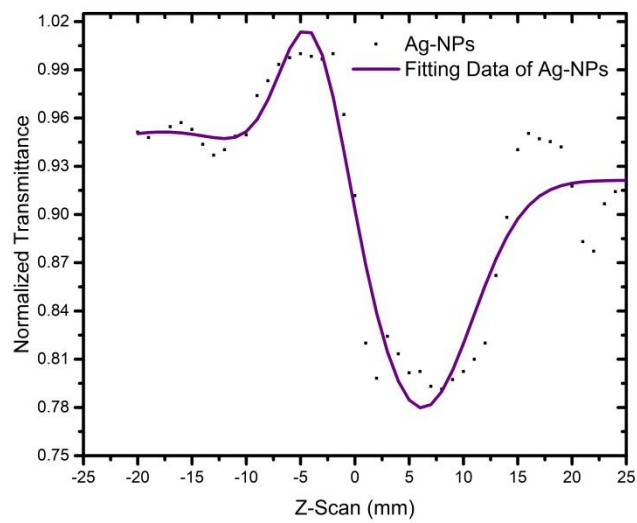
The different peak-valley values $\Delta T_{(p-v)}$ indicates different degree of NLR of the samples studied. The phase distortion $\Delta\Phi^0$ can be calculated from the differences between the normalized transmittance peak and valley, ΔT_{p-v} as shown in Equation (5): [1].

$$\Delta T_{(p-v)} = 0.406(1-s)^{0.27} \Delta\Phi^0 < \text{for } \Delta\Phi^0 < \pi(2) \quad (5)$$

The nonlinear refractive index, n_2 , can then be obtained from Equations (6) [20] :

$$\Delta\Phi^0 = \frac{2\pi L_{eff} n_2 I_0}{\lambda} \quad (6)$$

The evaluation of nonlinear absorption of Ag-NPs depend on open aperture measurement performed and normalized transmittances are shows trend in Figure 4(a). The nonlinear absorption coefficients of the of Ag-NPs are determined by valleys at focal point $\Delta T_{(z)}$. The nonlinear absorption coefficients show $4.87 \times 10^{-4} \text{ cm W}^{-1}$. For the evaluation of the refractive index (n_2) of samples Ag-NPs thin films are depends on the closed-aperture measurements and normalized transmittances are performed, as shown in Figure 4(b). The close-aperture Z-Scan shows transmission peaks followed by valleys near the focal point, which are asymmetric in trend. The Ag-NPs films reveal post focal peak and valley, which is a clear indication of negative lens effect of n_2 . The Ag-NPs show refractive index of n_2 is $-7.94 \times 10^{-9} \text{ cm}^2 \text{ W}^{-1}$ [1, 12, 21].

**A****B****Figure 4.** Open- aperture (A) and Closed-aperture (B) of Z-Scan curve for samples Ag-NPs.**Table 1.** Nonlinear Refractive Index and Nonlinear Absorption Coefficient for sample Ag-NPs Sample.

| Samples | PI(mW) | λ (nm) | w_0 (μ m) | I_0 (MWcm ⁻²) | α (cm ⁻¹) | $\Delta\Phi_0$ | n_2 (cm ² W ⁻¹) | β (cmW ⁻¹) |
|---------|--------|----------------|------------------|-----------------------------|------------------------------|----------------|--|------------------------------|
| Ag-NPs | 33 | 800 | 15.28 | 548.462 | 17.3×10^4 | 0.61 | -7.94×10^{-9} | 4.87×10^{-4} |

4. Conclusion

The metal of Ag NPs deposited using an e-beam evaporation system are reported, the UV-VIs take place to identify peak absorption, the nonlinear optical properties are measured by the Z-Scan method with a femtosecond laser. The Ag-NPs fabricate with randomly nanoparticles distributed which show absorption and predominantly contribute to large nonlinear absorption. Ag-NPs size appeared to affect nonlinear optics properties as well nonlinear absorption and nonlinear refraction. This research work has detailed simple and fast method to determine the nonlinearity of nanoparticles, and the results show Ag-NPs films could be a promising candidate as a nonlinear optical material.

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