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Amplitude-modulated acoustic waves by nonlinear optical signals in bimetallic Au-Pt nanoparticles and ethanol based nanofluids

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ABSTRACT

Acoustic waves were propagated through bimetallic Gold and Platinum nanoparticles suspended in ethanol in order to analyze their modification in amplitude by the assistance of third-order nonlinear optical effects. Nanosecond pulses at 532 nm wavelength were able to modify the acoustic transmittance by shifting the resonance of the mechanical vibration modes of the sample contained in a quartz cuvette. The optical Kerr effect exhibited by the nanoparticles was identified to be responsible for third-order optical nonlinearities that caused important changes in density associated with the sample. The nanofluids were prepared by a sol-gel method and explored by a vectorial two-wave mixing experiment. The nanostructured nature of the samples was evaluated by standard UV–Vis spectroscopy, high-resolution transmission electron microscopy and energy-dispersive X-ray spectroscopy measurements. Potential applications for developing optomechanic nanosystems sensitive to pressure driven by optical nonlinearities can be contemplated.

1. Introduction

Nanomaterials have fascinated the attention of scientific community regarding their unique structure and morphology with particular signatures for interacting with energy. In recent decades, nanoparticles (NPs) in liquid suspensions have been extensively studied in order to understand advanced properties exhibited by colloidal matter. Metallic NPs are attractive for designing photonic signal instruments taking into account that their optical properties are dependent on their distribution and composition parameters [1]. The shape and size exhibited by metallic NPs play a key role in physical and chemical effects since they determine their electromagnetic [2], mechanical [3], and catalytic properties [4]. Nonlinear optical (NLO) characteristics of metallic NPs are particularly suitable for developing ultrafast all-optical functions [5]. Multiphotonic processes can receive an enormous enhancement emerging from collective excitations of free electrons associated with Surface Plasmon Resonance (SPR) phenomena [6]. Moreover, from the preparation of metallic NPs by different processing methods, can result a variety of properties that can be controlled in a highly selective fashion [7].

Remarkably, Au NPs present a broad absorption band in the visible region that makes them useful for developing current biomedical applications [8], including molecular imaging [9], drug delivery [10], and plasmonic photothermal therapy [11]; among others. On the contrast, the pure Pt NPs exhibit their SPR absorption band located in the UV region of the electromagnetic spectrum; in this regard, Pt NPs are attractive for developing single-photon devices [12]. Besides, Pt NPs have been gaining special attention because of their potential in radiotherapy operations derived from their resistance to radiation [13].

Multimetallic NPs present additional advantages in comparison than monometallic NPs, owing to the synergistic effects that arise from the combination of the distinct metallic elements [14]. Specifically, bimetallic hybrid nanostructures may show different absorption resonances that represent the participation related to the two separated metals [15]. It is worth noting that several Au alloys integrating other metals, such as Pt, have been synthesized in order to improve exceptional features determined by metal components and structure [16]. It has been previously pointed out the powerful photocatalytic activity exhibited by Au-Pt NPs in energy development for photovoltaic cells and batteries [17]. Additionally, the assistance of bimetallic Au-Pt NPs promises outstanding biomedical and molecular sensing applications [18].

Biosensing techniques, which require highly sensitive biomolecular diagnostics, have been importantly impacted by the influence of NLO and photoacoustic (PA) effects for improving absorption spectroscopy systems and optoacoustic imaging evaluations [19]. However, optoacoustic methods used to be limited for in vivo studies, even though PA imaging promoted the detection of ultrasound waves generated when short laser pulses irradiate the target (human tissue) [20].

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In the era of nanotechnology, plasmonic NPs seem to be good candidates for PA imaging due to their fast and sensitive photonic response [21]. The optical forces induced by light-matter interactions enable trapping and controlling nanostructures based on the PA phenomena [22]. When the irradiated structure absorbs optical energy, a fast thermoelastic expansion can present an influence in a pressure wave [23]. The vibrational response of different bimetallic alloys has been analyzed for determining the behavior and properties of the elements studied [24].

Notwithstanding the above, recent advances that concern to bimetallic NPs have demonstrated their potential associated with their NLO properties and ultrafast response [25]. The interest for developing materials with optical nonlinearities has increased by considering promises for engineering all-optical processing devices and sensors [26]. In this context, this paper has been devoted to investigate the modulation in amplitude for acoustic waves by using nonlinear optical signals in bimetallic Au-Pt NPs and ethanol based nanofluids. In this work, we highlighted the effect of third-order optical nonlinearities in the automatic modification of the amplitude of acoustical signals through nonlinear materials. Potential applications related to plasmonic nanofluids for developing opto-acoustic instrumentation devices can be envisioned.

2. Materials and methods

2.1. Sample preparation

The preparation of bimetallic Au-Pt NPs in an ethanol solution was conducted by using a sol-gel route previously reported [27]. The synthesis process involves water/alkoxide with a molar ratio 0.8 and Titanium i-propoxyde [$Ti(OC_3H_7)_4$] with a concentration C = 0.05 mol/L featuring pH = 1.25. The relationship between bimetallic components was based on standard solutions of Au and Pt precursors with equivalent nominal metal concentration of 1000 mg/L each. The resulting molar ratio of the (Au + Pt)/$Ti(OC_3H_7)_4$ mixture was 0.76% (mol/mol) contained in a total volume of 11.5 mL. Direct photoreduction of Au and Pt ions contained in the sol-gel solution was performed by an ultraviolet reactor to finally obtain the Au-Pt NPs. Transmission Electron Microscopy and High-Resolution Transmission Electron Microscopy (TEM and HRTEM; JEM-ARM200CF&Gatan-Ultrascan 1000xP system) were undertaken by placing the sample in a Cu grid to atomic resolution operation with accelerating voltages of 80–200 kV. The bimetallic characteristics of the NPs were analyzed using an Energy-dispersive X-ray spectroscopy (EDX; JEOL JSM-7800F) in Scanning Transmission Electron Microscope (STEM) mode. In order to observe the absorption bands associated with the SPR of the bimetallic NPs, spectrophotometric measurements were carried out by using an Ocean Optics UV–Vis system.

2.2. Third-order nonlinear optical response and amplitude modulation of acoustic waves

In Fig. 1 is schematized the two-wave mixing experimental setup employed for measuring the third-order nonlinear optical effects and their influence on the propagation of acoustical signals through colloidal Au-Pt NPs. A Nd:YAG laser system (Continuum Model SL II-10) with green light pulses of 4 ns at 532 nm wavelength was employed as an optical source. The light pulses presented linear polarization. Pump and probe nanosecond waves were divided by a beam splitter, BS, at the output of the laser system to present an equal irradiance relation. The pulse energy employed was 100 mJ with repetition rate of 10 Hz during the experiments. In Fig. 1, M represents a mirror and PD1–2 are PIN photodetectors, respectively. The beam waist focused on the sample was 6 mm with a geometric angle of 30° separating both optical rays. Acoustical signals travelling through the nanofluids were controlled and delivered by an electronic sinusoidal generator (EG) and speaker (S); respectively. Acoustical data acquisition was carried out by a

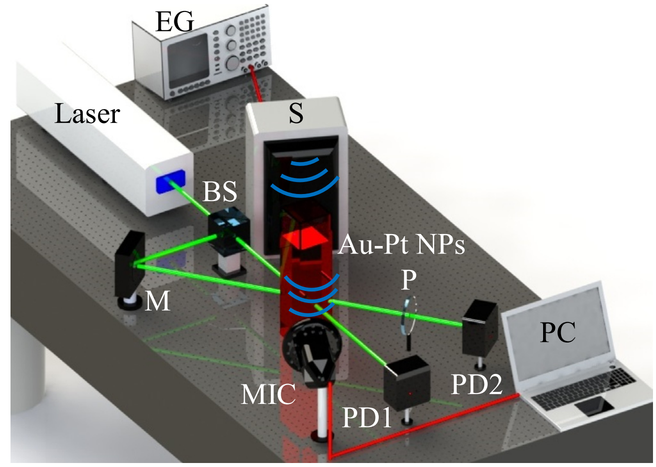

Fig. 1. Experimental setup for modulating acoustic signals in amplitude by the assistance of third-order nonlinear optical effects.

microphone (MIC) connected to a personal computer (PC) where the acoustic signal was recorded and analyzed by digital processing. The pump and the probe beams were described using the finite-differences method to numerically solve the wave-equation [28]:

$$\nabla^2 E_{\pm} = -\frac{n_{\pm}^2 \omega^2}{c^2} E_{\pm} \tag{1}$$

where the right and left circular components of the electric field are $E_{\pm}$ and $E_{\mp}$; respectively.

ω represents the optical frequency considering the approximation [28]:

$$n_{\pm}^2 = n_0^2 + 4\pi\left(A|E_{\pm}|^2 + (A+B)|E_{\mp}|^2\right) \tag{2}$$

where $A = \chi^{(3)}_{1122}$ and $B = \chi^{(3)}_{1212}$ and n_0 is the weak-field refractive index.

3. Results and discussions

Fig. 2 depicts the representative optical transmittance spectrum for the nanofluids studied. From the plot, it can be clearly observed two

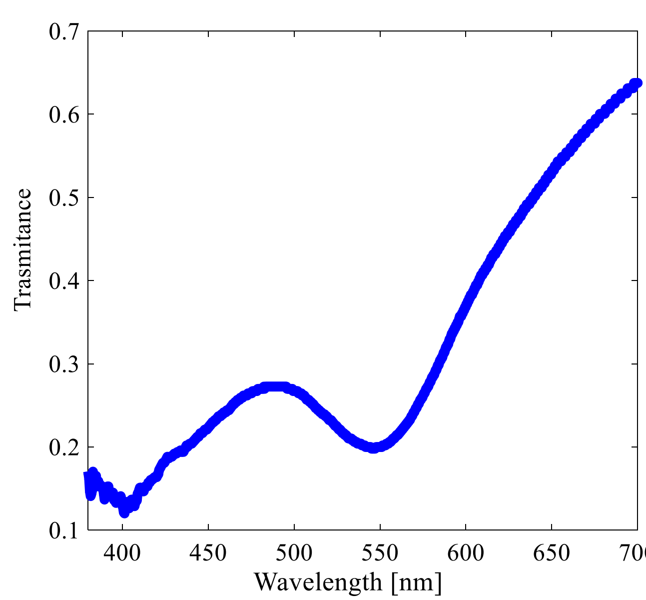

Fig. 2. Transmittance spectrum of bimetallic Au-Pt NPs suspended in ethanol.