Photonic Crystal Enhanced Photothermal Lens

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Abstract: We demonstrate a photonic crystal-based method that is capable of enhancing the photothermal lens effect generated by light absorbing materials. The method was used to analyze gold nanoparticles and exhibited stronger photothermal lens signals.
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Photothermal spectroscopy has been used to indirectly measure the sample absorbance through the detection of heat generation under light illumination of the sample. Several photothermal-based methods, such as the photothermal lens (PTL) and photothermal deflection, have been implemented for chemical analysis, microscopic study of nanoparticles, and biomolecule sensing [1, 2]. A typical PTL system measures the deflection of a probe beam caused by the refractive index gradient and elastic deformation of the optically heated sample [3]. In this work, we use a one-dimensional photonic crystal (PC) substrate comprised of a nanostructured dielectric thin film to develop a new PTL detection scheme. The PC substrate exhibits narrowband optical resonances owing to the guided-mode resonance (GMR) phenomenon [4]. As illustrated in Fig. 1(a), the probe beam is coupled into a GMR mode when the pump beam is off. When the pump beam is turned on, the change in the refractive index of the surrounding air in the vicinity of the pumped spot alters the incident angle of the probe beam, thereby decouples it from the GMR mode. As a result, the reflection of the probe beam drops dramatically. The measurement of the reflectivity change of the probe beam can be utilized to quantify light absorbing materials on the PC surface.

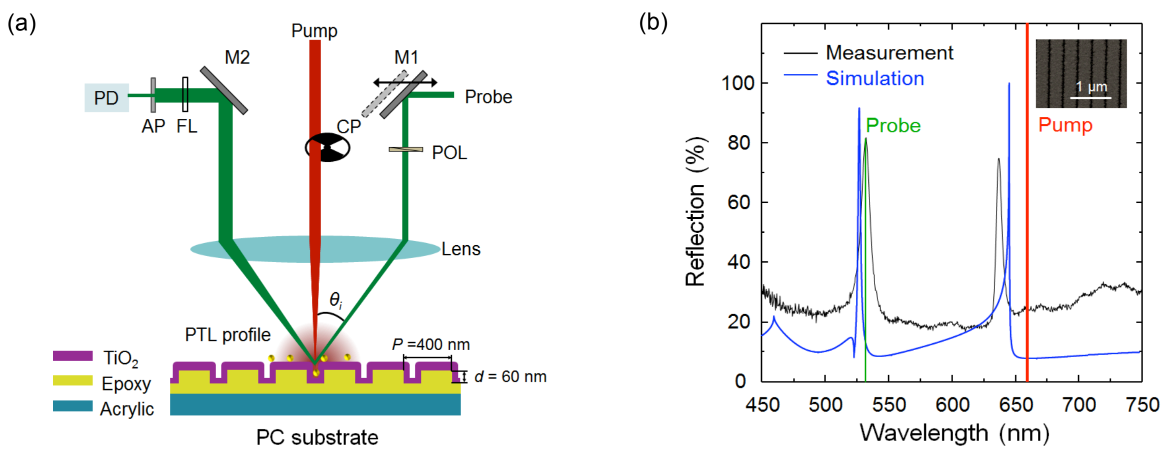

Fig. 1. (a) Schematic of PC-enhanced PTL setup. The grating structure has a period of Λ = 400 nm, a duty cycle of 60%, and a depth of d = 80 nm. A 100 nm-thick TiO_2 layer (n = 2.0) was coated onto the epoxy layer. The convex lens focuses the pump beam onto the PC and tunes the incident angle of the probe beam to a GMR and the photodetector measures the change in reflection when the pump beam is turned on. (b) PC reflection with respect to wavelength. The probe beam at 532 nm was coupled to one of a GMR mode. The pump beam at 660 nm was not coupled to a GMR mode to ensure better stability of the signal. The inset shows the SEM image of the PC surface.

The PTL scheme demonstrated here utilizes a PC substrate shown in Fig. 1(a). The PC consisted of a linear grating structure was fabricated using a low-cost nanoreplica molding process [5]. Briefly, the liquid ultra-violet curable epoxy was squeezed between a transparent acrylic film and a silicon mold, which bore a negative grating pattern. After the epoxy was cured by UV exposure, the substrate was peeled away from the silicon mold. Upon the acrylic substrate, the cured epoxy carries the desired grating structure. Subsequently, a high refractive index layer of TiO_2 was evaporated onto the PC surface to act as a light confinement layer. The PTL setup shown in Fig. 1(a) consists of a pump laser that emits at λ_{pump} = 660 nm with the power of P_{pump} = 240 mW, a convex lens (f = 50 mm) that focuses the pump beam onto the PC, a probe laser (λ_{probe} = 532 nm, P_{probe} = 5 mW) that detects the pump-induced changes around the PC surface, a linear polarizer that polarize the probe laser to TM mode, a mirror (M1) mounted on a linear translation stage that tunes the incident angle of the probe beam in order to couple it efficiently into a GMR mode, a bandpass filter (λ_c = 532 nm and $\Delta\lambda$ = 5 nm), an aperture (diameter of 2 mm), and a

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photodetector. The output of the photodetector was measured using an oscilloscope. During a test, the pump beam was switched on and off using a chopper. Fig. 1(b) compares the measured and simulated reflection spectra of the PC sample. The 532 nm probe beam was coupled to the GMR mode, which is labeled by the green line in Fig. 1(b). The spectral position of the pump beam is which is not coupled to any GMR mode.

To test the feasibility of the proposed PTL scheme, we measured the PTL signals of an absorbing dye (Epolight 6661) on a PC substrate at a concentration of 1.0 mg/mL. Fig. 2(a) shows the change of probe beam reflection when the pump beam was switch on and off. To demonstrate the enhancement of PTL signal by the PC, we measured the PTL signal as a function of the incident angle of the probe beam. The PTL signals and probe laser transmission through the PC are shown in Fig. 2(b), where the minimum transmission represents the GMR mode. It can be seen that there is a strong correlation between the PTL signal and the GMR mode.

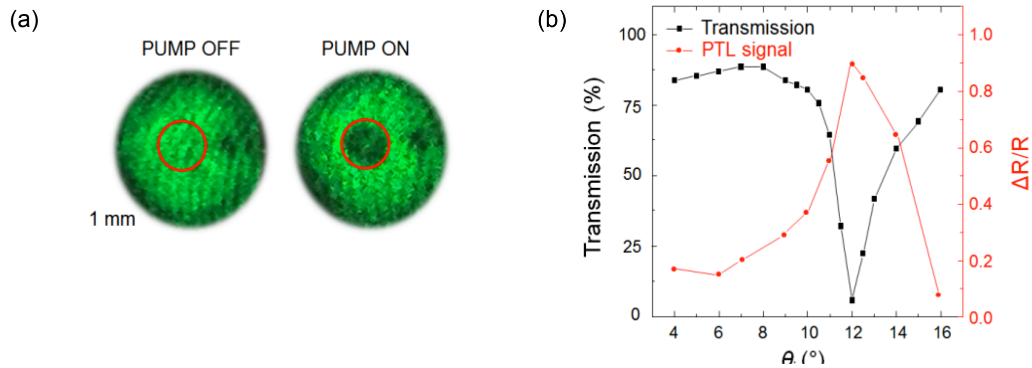

Fig. 2 Measurements of the PTL signal. a) Photographs of the reflected probe beam taken when the pump is switched off (left panel) and on (right panel). b) Transmission of the probe laser through the PC substrate and the PTL signals as a function of the incident angle.

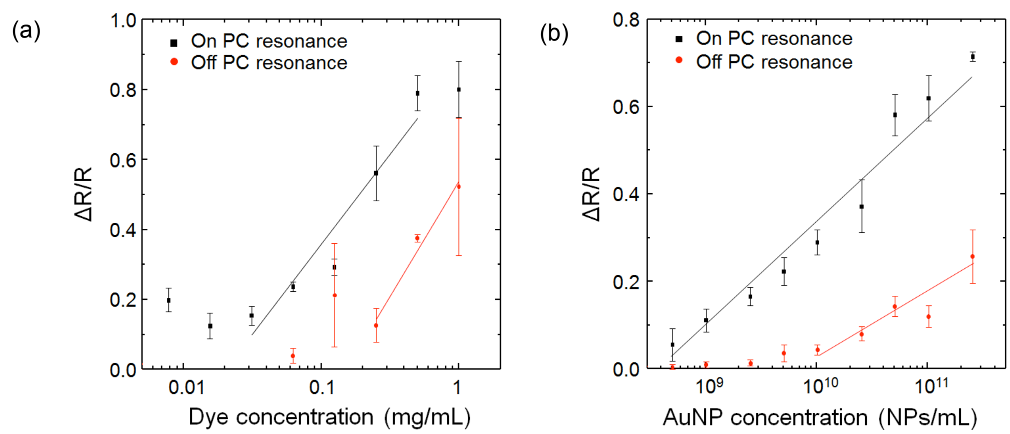

Fig. 3. Measured PTL signals for (a) dye molecule and (b) AuNP at a serial of concentrations. The improvement of detection limit was 8-fold for dye molecule and 20-fold for AuNPs.

Next, we measured the PTL signals of the dye and gold nanoparticles (AuNPs) at a serial of concentration. The samples were measured under both on and off resonance conditions. For the detection of the dye, the detection limit is improved from 0.25 mg/mL (off PC resonance) down to 0.031 mg/mL (on PC resonance). In the case of AuNPs, the detection limit is reduced from 1×10^{10} NPs/mL to 5×10^{8} NPs/mL, which represents a 20-fold improvement. Currently, we are testing the capability of using the PC-enhanced PTL approach for chemical analysis. The pump-probe system shown in Fig.1 (a) is modified by replacing the pump laser with a tunable mid-infrared laser. The results of the mid-infrared spectroscopic measurement will be reported at the conference.

References

[1] A. C. Boccara, D. Fournier, W. Jackson and N. M. Amer, "Sensitive photothermal deflection technique for measuring absorption in optically thin media," *Opt. Lett.* **5**, 377-379 (1980).

[2] A. V. Brusnichkin, D. A. Nedosekin, M. A. Proskurnin and V. P. Zharov, "Photothermal lens detection of gold nanoparticles: Theory and experiments," *Appl. Spectrosc.* **61**, 1191-1201 (2007).

[3] R. D. Snook and R. D. Lowe, "Thermal lens spectrometry. A review," *Analyst* **120**, 2051-2068 (1995).

[4] Y. Ding and R. Magnusson, "Use of nondegenerate resonant leaky modes to fashion diverse optical spectra," *Opt. Express* **12**, 1885-1892 (2004).

[5] C. Ge, M. Lu, X. Jian, Y. F. Tan and B. T. Cunningham, "Large-area organic distributed feedback laser fabricated by nanoreplica molding and horizontal dipping," *Opt. Express* **18**, 12980-12991 (s).