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Laser-induced Bessel beams can realize fast all-optical switching in gold nanosol prepared by pulsed laser ablation

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We demonstrate the possibility of realizing, all-optical switching in gold nanosol. Two overlapping laser beams are used for this purpose, due to which a low-power beam passing collinear to a high-power beam will undergo cross phase modulation and thereby distort the spatial profile. This is taken to advantage for performing logic operations. We have also measured the threshold pump power to obtain a NOT gate and the minimum response time of the device. Contrary to the general notion that the response time of thermal effects used in this application is of the order of milliseconds, we prove that short pump pulses can result in fast switching. Different combinations of beam splitters and combiners will lead to the formation of other logic functions too.

OCIS codes: 140.0140, 140.6810, 160.3380, 160.4236, 190.4870, 250.5403, 350.6830.

1. INTRODUCTION

All-optical logic operations are necessary for optical processing systems to avoid cumbersome electro-optic conversion. Many materials, concepts, and technologies have been studied and developed to realize all-optical switching such as self-electro-optic devices, laser-induced optical devices, and microelectromechanical systems (MEMS). However, the all-optical regime is still not in a position to completely replace the electronic counterparts in switching. The most current "optical" devices are based on optically interfaced electronics in which the electronic core does the switching. However, optical switching has a future inside digital machines if the concept is simple and not power consuming. There is a report regarding the superposition of light beams in semiconductors and the simple use of their intrinsic and extrinsic features such as free-carrier absorption, lifetime of excited carriers, and impurity absorption and related properties to cause an optical switch [1]. In this way, optical switching was demonstrated by using the infrared absorption of a pulsed Nd:YAG laser in silicon, and a hybrid bistable device was realized by superposing the emission of a green light-emitting diode (LED) and a He–Ne laser in a cadmium sulfide (CdS) crystal. There is a recent report on the realization of an all-optical logic AND–NOR gate based on cross-gain modulation that requires only one semiconductor optical amplifier to perform the logic gate with three input signals. The switching time reported was about 650 ps for the rise time and 100 ps for the fall time [2]. There is also a report regarding all-optical logic gates containing a local nonlinear Mach–Zehnder interferometer waveguide structure. Here, the light-induced index changes in the Mach–Zehnder waveguide structure make the output signal beam propagate through different nonlinear waveguides. Based on the output signal beam propagating property, various all-optical logic gates like XOR/NXOR, AND/NAND, and OR/NOR were obtained by using the local nonlinear Mach–Zehnder waveguide interferometer structure with two straight control waveguides [3].

In this paper, we report the possibility of realizing all-optical logic functions in a lab setup by making use of self- and cross-phase modulations of light beams. For this purpose, we make use of two overlapping beams having Gaussian intensity distribution. As the high-power beam propagates through the absorbing medium, it experiences phase change due to various processes like photothermal effect, self-focusing, or defocusing, etc. Since the low-power beam is overlapping this, it will have an induced phase shift due to the first beam, and depending on the strength of the phase modulation the Gaussian beam will be converted to Bessel beams of various orders. This is illustrated in the photograph shown in Fig. 1. The novelty of the work is that, unlike in usual photothermal effects that rely on thermal diffusion, which has a slow response, we have proved that it is possible to obtain a fast all-optical switch using instantaneous thermal effects that depend on the pulse duration of the pump beam. This will ultimately make simple configurations for fast all-optical switches using two laser beams.

2. EXPERIMENTAL TECHNIQUE

When a spatially Gaussian pump is used, the interaction of light with matter is stronger at the central part of the laser beam than the edges and as a result, a probe beam which spatially overlaps the pump beam is perturbed spatially and inhomogeneously. The spatially inhomogeneous

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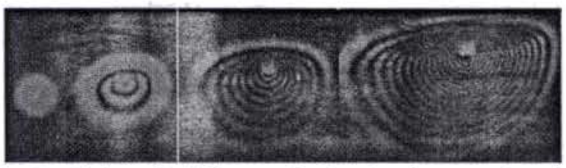


Fig. 1. (Color online) Photographs showing the conversion of a Gaussian beam to Bessel beams of various order depending on the magnitudes of the phase modulation induced by the optical beam.

interaction induces a distortion in the phase and spatial profile of the beam. This intensity-dependent perturbation is caused due to intensity-dependent refractive index or absorption change of the medium referred to as thermal lensing (TL). It is a photothermal effect and results when energy from the laser beam is absorbed by the sample, causing heating of the sample along the beam path. The lens is created through the temperature dependence of the sample refractive index. The lens usually has a negative focal length, since most materials expand upon heating, and the refractive index is proportional to density. This results in divergence of the beam and is detected as a decrease in power at the center of the beam [4]. Depending on the refractive index of the medium, we can tune the phase modulation and control the order of the Bessel beam resulting from the axicon effect of the sample. It is also possible to generate and dynamically reconfigure the Bessel beams [5]. When illuminated with a Gaussian laser beam, our fluidic axicon generates a diverging beam with an annular cross section. By varying the refractive index of the solution or the pump power, we can easily vary the spatial properties of the resulting Bessel beam. There is a report on numerical work on the propagation of Bessel beams through turbulant media [6] and also on the application of these beams for a biophotonic workstation [7].

Thermal diffusivity is an important parameter that controls the rate at which heat may flow through the medium; therefore, it is an important factor that determines the speed with which we can perform the logical functions. If we rely on the steady-state TL, then obviously the gate will have only microsecond to millisecond response time. However, with a pulsed laser as the excitation source, we get a transient TL and the rate of radiationless transition is very fast in comparison with the decay rate of the TL. In other words, we can make use of the instantaneous TL and reduce the response times to the order of a few tens of nanoseconds. We demonstrate this phenomenon using gold nanosol prepared by pulsed laser ablation. This technique yields chemically pure and stable gold nanoparticles in the required environment. Gold is preferred over other metallic nanostructures because of its chemical inertness and photostability. Unlike most common dyes, it does not undergo bleaching.

A thin gold plate is kept immersed in 20 ml double-distilled water in a beaker. The Gaussian beam from the Nd: YAG laser (Quanta Ray, Spectra Physics) at 1064 nm and pulse width of 10 ns is tightly focused from above onto the sample surface by using a 80 mm lens. The average power of the beam is 500 mW. This gold plate is ablated for 7 min. After 7 min. there is a visible change in color. The solution had turned purple blue, indicating the formation of gold nanoparticles. An absorption spectrum of the solution shows plasmon peak at 527 nm, and x-ray diffraction (XRD) analysis confirms the particle size to be ~5 nm. (see Fig. 2).

The basic experimental setup to form thermal lens is described in [8]; we modify it suitably to realize the NOT gate. Since the gold sol has peak absorption wavelength in the green region, a diode-pumped solid-state (DPSS) laser [BWT 50 (B&W) TEK, 532 nm] was used as the pump laser source or the logic input to the gate. A low-power He–Ne laser (632.8 nm) was used to get the output of the gate. The pump beam, which is modulated by the chopper, is absorbed by the sample. This causes heating of the sample and thus creates a thermal lens. This lens formation diverges the probe beam, which is detected and collected by an optical fiber tip connected to a photodetector fed to a digital storage oscilloscope (DSO). Initially, the sample is kept at the focal point of the 20 cm convex lens. Then it is translated along the beam propagation direction to fix at the position where the TL signal strength is maximum. An optical fiber was used to receive the central portion of the beam because the total intensity of the probe beam is just redistributed in thermal lensing so that if we collect the entire beam intensity, the logical operation is not possible. The logic 1 and 0 obtained for nanogold in water are shown in Fig. 3. The logic 1 output is

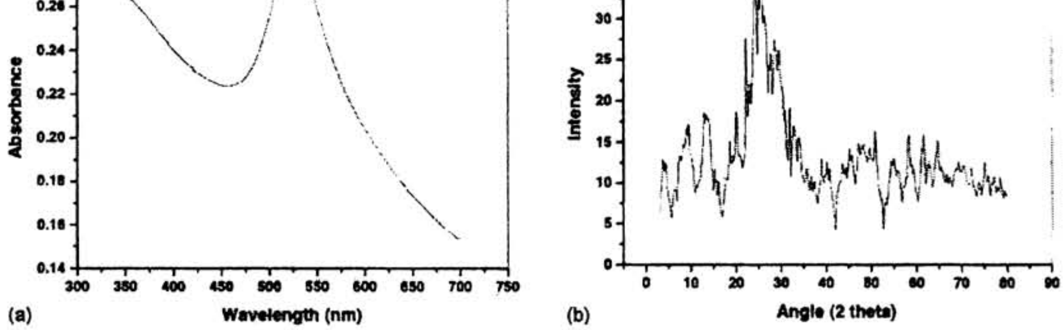


Fig. 2. Absorption spectrum and XRD of gold nanoparticles in water.

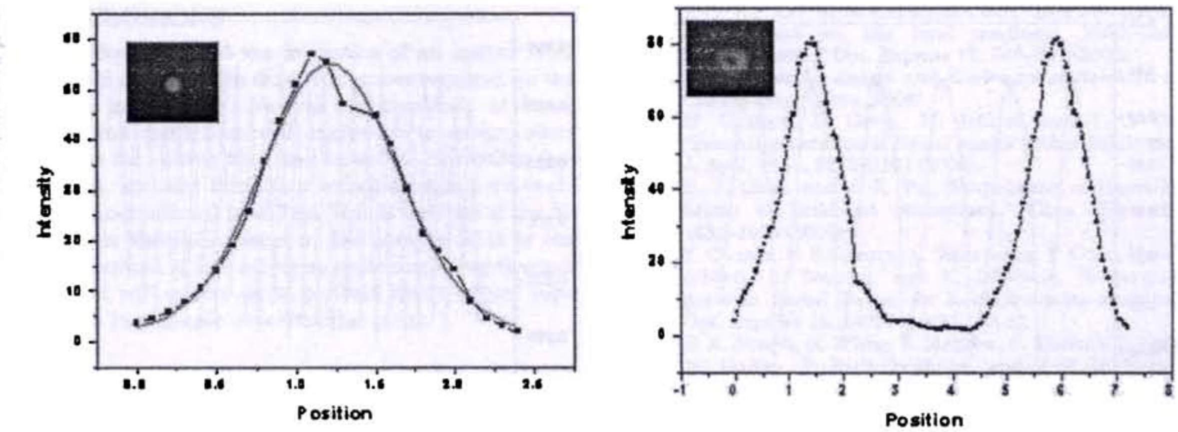
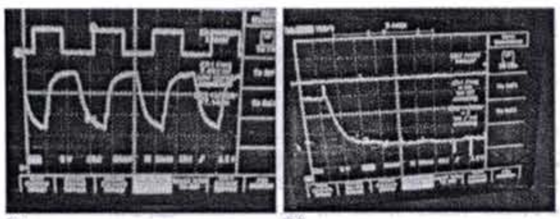


Fig. 3. (Color online) Logic 1 and logic 0 are interpreted as the probe beam intensity measured by the detector. When the pump is off (logic 0 input) the probe beam does not diverge, resulting in logic 1 output.



(a) (b)

Fig. 4. (Color online) (a) Oscilloscope traces showing square pulses from the pump and the corresponding probe beam. When the pump is high, probe is low. The traces were recorded before triggering. (b) Decay of the probe when pump is turned on. Probe reaches a steady state decided by the characteristic time constant.

provided by the Gaussian probe beam for no pump (logic 0 input). However, when the input is 1, the TL causes the probe to expand with a central dark spot, corresponding to a first-order Bessel function. The intensity distribution and the probe beam profile are as in Fig. 3. Figure 3(a) shows the probe beam intensity distribution when the pump is off. It is a Gaussian function. The corresponding photograph is given in the inset. However, when the pump is turned on, the probe shows a logic 0 as can be seen from the photograph in Fig. 3(b). The measured intensity distribution shows a minimum at the center corresponding to a first-order Bessel function. There is an optimum intensity of the pump beam, which can cause thermal lensing. So, to measure the threshold pump power, we measured the photodetector output for various pump power. The readings were taken for the probe beam when the pump was set to OFF and ON, respectively. Sample oscilloscope traces are shown in Fig. 4, which clearly demonstrates switching.

3. RESULTS

Using DPSS laser with continuous wave output, we first studied the steady-state TL effect and the NOT gate operations for various pump power and intensity modulation frequencies. A half-wave plate and polarizer were used for intensity control. This was also done for various concentrations of gold sol, since higher concentration will help in obtaining lower threshold power. It is found that the TL signal strength increases with increase in concentration of gold sol for any chopping frequency. The observation that the beam diverges in the presence of the pump, points to the fact that the plasmonic oscillations in gold relaxes through thermal waves released to the medium. It is also a supporting evidence for the presence of greater nonradiative decay channels for any dye molecules adsorbed on nanometal surface, which is the basic idea behind surface-enhanced spectroscopy. The gate operations are concluded in Table 1, which shows threshold input power for various concentrations. It is seen from the table that as the pump power decreases, the TL effect weakens, thereby increasing the probe power at the detector. With different attenuators and the half-wave plate–polarizer set, we reduced the pump power and observed the spatial probe beam profile on a screen and measured the corresponding voltage at the detector. It was found

Table 1. Probe Beam Power Detected by the Photodetector (mV) for Various Input Power in mW[a]

	Probe Beam Output (V) for Pump Power of (mW)						
Au Concentration	1.5	4.8	15.3	20.4	35.7	70.2	99.3
0.68 mM	0.301	0.285	0.131	0.108	0.089	0.084	0.082
0.74 mM	0.295	0.283	0.130	0.103	0.084	0.083	0.081
0.82 mM	0.283	0.280	0.127	0.101	0.081	0.080	0.081
0.90 mM	0.281	0.275	0.126	0.099	0.080	0.078	0.080
1.00 mM	0.280	0.272	0.122	0.097	0.077	0.073	0.080

[a]For no pump, probe output is 0.328 mV.

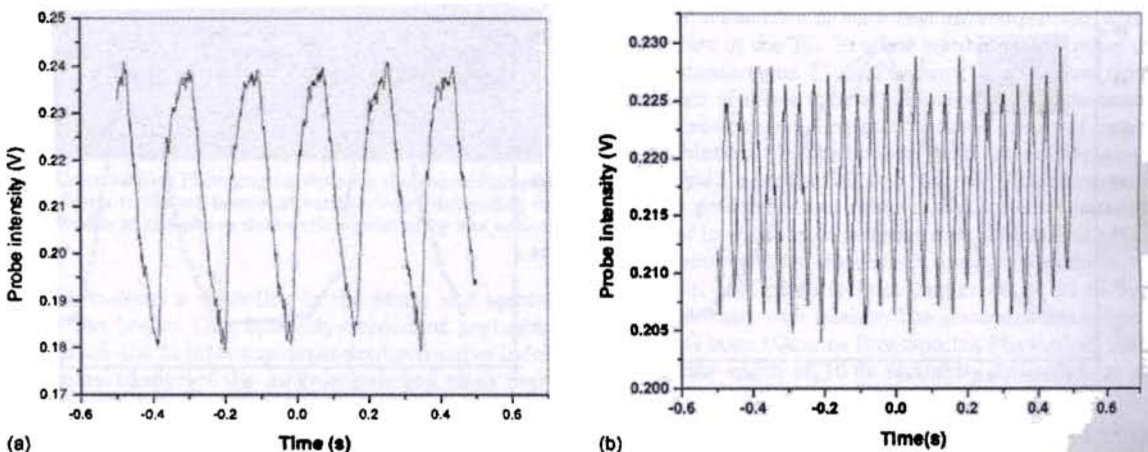


Fig. 5. (a) The probe beam amplitude versus time for pump-chopping frequency 6 Hz and (b) at chopping frequency 25 Hz. The switching time is less for the higher frequency.

that a minimum pump power of 15.3 mW is required to make a clear decrease in the on-axis probe beam intensity. About 40% reduction in voltage is necessary to switch from logic 1 to logic 0.

For measuring the switching time for various pulse lengths of the pump, we recorded the probe beam intensity over time for various modulation frequencies of the pump. Two examples are shown in Fig. 5 from which it is obvious that the TL effect for longer excitations is not instantaneous and takes finite time to build up. The chopper is used to modulate the pump beam to study the formation and decay of the TL signal during the ON and OFF states of the pump source. When the pulse width of the pump beam is higher, there will be more heating of the sample, which will subsequently delay the decay time of the TL signal. So, with higher chopping frequency and therefore smaller pulse width, the switching time of the gate will be faster. To obtain high response time, nonlinear optical effects are generally used [9–11].

To find out the effect of a pulsed laser source on the response time of the gate, we performed the experiment using the second harmonic of an Nd:YAG laser. The time-dependent probe beam intensity is obtained using a nanosecond photodetector connected to 1 GHz DSO. This is as shown in Fig. 6(a). Clearly, the probe closely follows the trigger in time response. Obviously, the shorter pulse quickly switches the probe to a logic 0 state due to the instantaneous TL effect which has a response time of nanoseconds. In our case we measured the switching time to be 600 ns [see Fig. 6(b)]. This experiment confirms the possibility of obtaining fast all-optical switching using photothermal effects. However, the ultimate objective will be to realize integrated optical circuit components for which miniaturization of the device will be required in addition to fabrication of samples as thin film, which will offer reduction in size and also stability of the material. For this, it is possible to integrate the gold nanoparticles in polymer and obtain thin films using spin-coating techniques. Our initial studies show that these structures are also capable of exhibiting cross-phase modulation and thus perform switching functions. Detailed studies are underway.

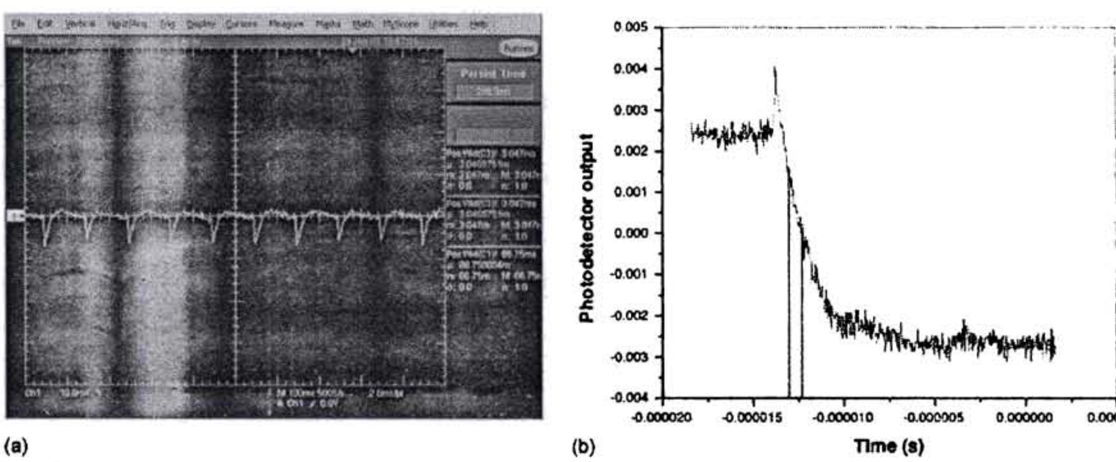


Fig. 6. (Color online) (a) Oscilloscope traces showing the fast switching of the gate for ns pump. (b) The switching time is measured as the difference between the 90% and 10% of the maximum between the two straight lines marked on the graph. It is around 600 ns.

4. CONCLUSIONS

We have demonstrated the formation of an optical NOT gate in gold nanosol. The threshold power required for the operation is 15.3 mW. Various combinations of beam splitters and combiners will enable us to design other logic gates too. Using ns pump laser we can realize fast logic gates, and the minimum switching speed we could obtain in gold nanosol is 600 ns. This is because of the instantaneous thermal effects in the sample. This is our first observation of fast response switching using thermal effects and will enable us to perform many optical logic operations in a simple experimental setup.

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REFERENCES

1. A. Erlacher, H. Miller, and B. Ullrich, "Low-power all-optical switch by superposition of red and green laser irradiation in thin-film cadmium sulfide on glass," J. Appl. Phys. **95**, 2927–2929 (2004).
2. S. Ammar, T. Joseph, and M. Pascal, "All-optical logic AND-NOR gate with three inputs based on cross-gain modulation in a semiconductor optical amplifier," Opt. Commun. **265**, 322–325 (2006).
3. Y.-D. Wu, T.-T. Shih, and M.-H. Chen, "New all-optical logic gates based on the local nonlinear Mach–Zehnder interferometer," Opt. Express **16**, 248–257 (2008).
4. B. S. Larkin, in *Lasers and Electro-optics Research at the Cutting Edge* (Nova, 2006).
5. M. Graham, D. Gavin, M. Jeffries, and T. C. Daniel, "Tunable generation of Bessel beams with a fluidic axicon," J. Appl. Phys. **92**, 261101 (2008).
6. B. S. Chen, and J. X. Pu, "Propagation of Gauss-Bessel beams in turbulent atmosphere," Chin. Phys. B **18**, 1033–1039 (2009).
7. T. Cizmar, V. Kollarova, X. Tsampoula, F. Gunn-Moore, W. Sibbett, Z. Bouchal, and K. Dholakia, "Generation of multiple Bessel beams for a biophotonics workstation," Opt. Express **16**, 14024–14035 (2008).
8. S. A. Joseph, H. Misha, S. Mathew, G. Sharma, Soumya, V. M. Hadiya, P. Radhakrishnan, and V. P. N. Nampoori, "Thermal diffusivity of rhodamine 6G incorporated in silver nanofluid measured using mode-matched thermal lens technique," Opt. Commun. **283**, 313–317 (2010).
9. J. Wang, Q. Sun, J. Sun, and X. Zhang, "Experimental demonstration on 40 Gbits/s all-optical multicasting logic XOR gates for NRZ-DPSK signals using four-wave mixing in highly nonlinear fiber," Opt. Commun. **282**, 2615–2619 (2009).
10. M. Yuji, K. Ikeda, H. Tobioka, T. Inoue, S. Namiki, K.-I. Kitayama, "Ultrafast all-optical logic gate using a nonlinear optical loop mirror based multi-periodic transfer function," Opt. Express **16**, 2570–2577 (2008).
11. T. Huiping, "Bright and dark solitons in quadratic nonlinear periodic structures and application to an all-optical logic gate," J. Phys. B **40**, 1391–1402 (2007).