Surface-plasmon-coupled semiconductor diode-laser package for refractive index sensing

Qiaoqiang Gan[1,2] and Filbert J. Bartoli[1,*]

[1]*Center for Optical Technologies, Lehigh University, Bethlehem, Pennsylvania 18015, USA*
[2] *qig206@lehigh.edu*
**Corresponding author: fjb205@lehigh.edu*

Received April 8, 2009; revised June 11, 2009; accepted June 11, 2009;
posted June 18, 2009 (Doc. ID 109730); published July 10, 2009

We combine plasmonic grating structures with semiconductor laser-diode packages to realize a prototype of miniaturized chemical/biosensor. The advantages of such a device include compact size, low cost, energy effectiveness, long device lifetime, stable performance, and label-free sensing, which should have commercialization potential. © 2009 Optical Society of America

OCIS codes: 240.6680, 230.7370, 050.2770, 260.3910.

Surface plasmons (SPs) are coherent oscillations of conduction electrons excited by electromagnetic radiation at the metal–dielectric or semiconductor–dielectric interfaces. It was believed that plasmonic structures and devices operating in the optical domain offer advantages for applications in biosensing. Surface-plasmon resonance (SPR) is sensitive to the refractive index change at a flat metal interface, and SPR sensors have been commercialized for a long time [1]. A major drawback of SPR sensing for applications requiring lightweight, portable systems is that the commercially available instrumentation can be expensive and too bulky to be portable. For example, it is difficult to imagine that commercial instruments weighing over 40 kg [2] could conveniently serve as portable instrumentation for point-of-care diagnostics. In recent years, researchers explored various designs to miniaturize the SPR system for portable sensing [3–6]. Nanostructured plasmonic biosensors, employing nanoscale hole arrays, gratings, and other novel topographies, could be an attractive platform for sensitive, label-free monitoring of cellular processes [7,8]. When receptor molecules are immobilized on the nanostructured metal surface, the binding of target biomolecules changes the local refractive index, affecting the optical properties of the SP modes and permitting optical detection [9,10]. What makes nanoplasmonic structures particularly interesting for biosensing is their ability to confine light spatially within subwavelength dimensions, and the observation of extraordinary light transmission through nanohole arrays [11] and related structures that greatly exceed that predicted by classical optical theory [12]. Other novel properties reported for nanoplasmonic structures, such as super lenses [13], bidirectional splitters [14], and the slowing of light [15,16], may open up new possibilities for biosensing [7,17]. Recently, some groups have successfully employed periodic nanoplasmonic structures in biosensing applications [7–10].

Semiconductor laser diodes (LD) are widely used in optical data storage, display, lightening, optical communications, etc. The advantages of the semiconductor LDs are compact size, low cost, energy effectiveness, long lifetime, and stable performance, thus rendering them portable or even potentially drone carried [18]. In this Letter, we integrated a nanoplasmonic structure at the output window of a semiconductor LD to design a novel sensor. By combining the advantages of semiconductor LDs and SP-based sensing, such devices should have great commercialization potential with wide applications for chemical/biosensing and environmental sensing (for example, sensing of water quality).

We first describe the structure of a standard LD, e.g., in a TO-5.6 package, in which the laser output is emitted from the front facet of a semiconductor LD. A built-in photodiode monitors the beam intensity emanating from the back facet of the LD. Our device is based on such a compact commercially available LD package (SANYO DL-3147-031, TO-5.6 package, wavelength=650 nm). We deposited a 220-nm-thick gold film on the output window of the LD and employed focused ion-beam milling (FEI DB 235) to fabricate nanograting structures on the metal film. The period and width of the gratings are about 330 nm and 70 nm, respectively [see Fig. 1(a)]. The area occupied by the gaps of the gratings is about 2% of the output window. The output laser beam is linearly polarized. To study the polarization dependence of these plasmonic grating structures, we fabricated gratings on two LDs with orthogonal grating orientations. One grating is parallel to the laser polarization direction [see Fig. 1(b)], and the other is perpendicular to that direction. In principle, only when the grating direction is perpendicular to the polarization direction

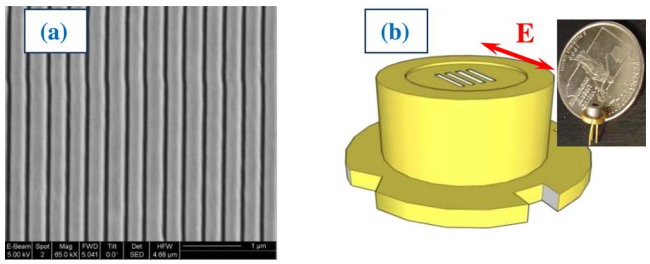

Fig. 1. (Color online) (a) SEM of the nanostructure. (b) Schematic of a plasmonic LD sensor in which the grating is parallel to the polarization direction of the laser beam. Inset, a real device.

of the laser beam could the SPP be excited, as will be shown by our experimental results in the next paragraph.

In current plasmonic LD sensor architecture, the wavelength of the incident beam is fixed at 650 nm, and the beam is incident on the plasmonic aperture approximately normal to the surface. Consequently, we employ the intensity modulation principle to measure the strength of the coupling between the incident light wave and an SP mode at a single wavelength and a fixed narrow range of incident angles [19]. The intensity of the reflected or transmitted light wave serves as the sensor output. Here we employ liquids with different refractive indices to demonstrate the sensitivity of the plasmonic LD structure. The refractive index was varied from 1.3 to 1.65, as shown in Fig. 2. There are two signal channels to observe the surface property changes; the first one is reflection signal channel. When the output window is covered by a metal film, most of the output beam will be reflected and monitored by the photodiode. When the reflected signal changes because of the refractive index change at the window surface, we observe a change in signal from the photodiode in the LD package. In this case, a chemical/biosensor function could be achieved by observing the reflected light signal. The second one is the transmission signal channel. Since the transmission properties of a metal grating can be tuned through the change of the refractive index on top of the nanostructures [7–10], the transmitted signal is another important means of monitoring the surface chemical behavior. In the measurement, we observe obvious transmission signal enhancement when the refractive index is increased [see the dots in Fig. 2(b)].

To better understand the relations between the transmission/reflection signal and the refractive index of the material at the interface measured in Fig. 2 (see the dots), the finite-difference-time-domain (FDTD) method is employed to model the transmission/reflection signal from the nanostructured surface (see the solid curves in Fig. 2). In this modeling, the permittivity of Au metal is set to $-9.8949+i1.0458$ at the 650 nm operating wavelength [20]. As shown in Fig. 2(b), when the refractive index increases, more light will be transmitted through the nanogaps of the grating structure. Generally, the simulated relations between the transmission/reflection signal and the refractive index of the material at the interface are in qualitative agreement with the measurement results shown in Fig. 2. However, many real factors cannot be counted in the simulation, such as surface roughness, nanofabrication error, and scattering within the LD package, which may lead to the difference between the simulation and measurement results.

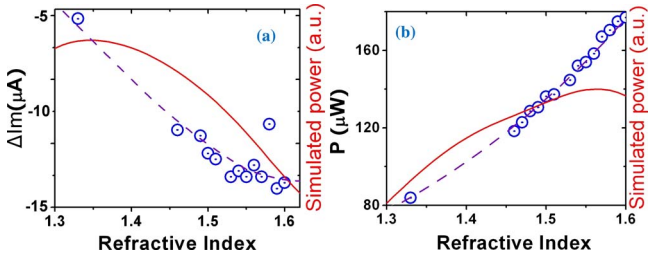

Fig. 2. (Color online) Performance of the plasmonic LD sensor: (a) ΔI_m (μA) is the monitor current change between the signal without/with the refractive index liquid. (b) P (μW) is the output power from the window with different refractive index liquids on it. The dots are measurement results. The dashed curves are plotted to guide the eyes, and the solid curves are FDTD modeling of the reflection and transmission signals versus the refractive index of the liquid covered on the structure surface. In this modeling, the depth of the Au film is set to be 220 nm, and the period and width of the gratings are set to be 330 nm and 70 nm, respectively, consistent with the sample parameters shown in Fig. 1(a). The grid size in the z direction is $\Delta z=10$ nm and in the x direction is $\Delta x=10$ nm. A periodic boundary condition is used in the x direction, and a perfect-matched layer boundary condition is used in the z direction.

Finally, we conduct a real-time measurement to monitor the refractive index change on the surface continuously. When we change the material from air ($n=1.0$) to water ($n=1.33$) then to oil ($n=1.46$), we observe an obvious change in the reflection signal for light polarized perpendicular to the grating grooves. On the other hand, if the grating direction is parallel to the laser polarization direction, SPP cannot be excited. Consequently, no obvious signal change is observed; see the upper line in Fig. 3. In addition, such a response to refractive index change was not observed with a standard LD with no nanostructures.

One of the key motivations for plasmonic sensor study is to realize high detection sensitivity. However, for the current plasmonic LD sensor architecture, the sensitivity and resolution are limited by device performance, especially that of built-in photodiode in the LD package, whose original function is to monitor the output power from the back facet of the LD. Since there is a large background signal in the reflection channel, the noise of the photo-

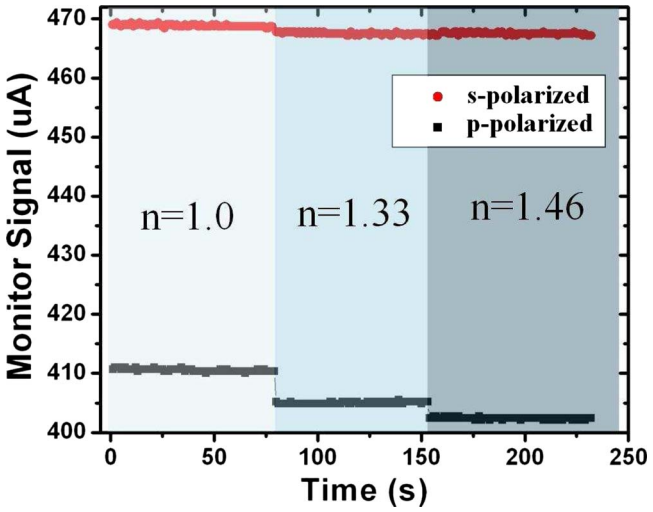

Fig. 3. (Color online) Performance of the plasmonic LD sensor in reflection mode as a function of time. For p polarization (the grating is perpendicular to the polarization direction of the laser), the monitored signal changes when the refractive index of the material on the plasmonic gratings is changed. For s polarization (the grating is parallel to the polarization direction of the laser), no appreciable signal change is observed (see the upper line).

diode, which is around 0.2 μA, limits the sensitivity and resolution in the reflection channel of this plasmonic LD sensor. Any signal change smaller than this value cannot be resolved in this measurement. Consequently, based on the experimental data (dots) in Fig. 2(a), the smallest detectable refractive index change in the reflection channel can be estimated to be about 0.008. The present value cannot compete with commercially available SPR sensors. Some improvement can be achieved by replacing the built-in photodiode with a higher-performance device. In the transmission channel, we employed a higher-performance power meter (Thorlabs PM100 with an S140A sensor head) to monitor the signal, where the noise was about 0.1 μW. Based on the data in Fig. 2(b), the smallest detectable refractive index change in the transmission channel is about 0.0004, which confirms that the built-in photodiode device performance limits the sensitivity of the reflection channel.

To optimize the performance of the plasmonic LD sensor further, two potential approaches are under investigation. The first one is to design the nanostructures to narrow the linewidth of the transmitted light. Since this plasmonic LD sensor employs intensity modulation to observe the signal change [19], a narrower transmitted linewidth will lead to a larger signal change for a given refractive index change [21]. The second approach is to optimize the coupling from the incident light to SP modes confined at the sensor surface. Since the incident beam is roughly perpendicular to the output plane in this plasmonic LD sensor architecture, the incident light may not be effectively coupled to the SP modes. Consequently, it is important to study the SP coupling issue with roughly normal incidence. This also applies to the results of recent reports [9,10,22–26] in which researchers monitored the transmission through the hole or slit arrays as a sensing signal.

In conclusion, we have realized a prototype SP-coupled semiconductor LD package for refractive index sensing. The surface property changes could be observed through transmission and reflection signal channels. The advantages of such a plasmonic LD sensor include compact size, low cost, energy effectiveness, long device lifetime, stable performance, and label-free sensing, which should have commercialization potential. We believe that it will find critical applications in state-of-the-art research and the biosensing market, such as a flying plasmonic head [27] for a lab on a CD [28].

References

1. K. A. Willets and P. Van Duyne, Annu. Rev. Phys. Chem. **58**, 267 (2007).
2. http://www.biacore.com/lifesciences/products/systems_overview/x100/system_information/index.html
3. A. N. Naimushin, S. D. Soelberg, D. U. Bartholomew, J. L. Elkind, and C. E. Furlong, Sens. Actuators B **96**, 253 (2003).
4. T. M. Chinowsky, J. G. Quinn, D. U. Bartholomew, R. Kaiser, and J. L. Elkind, Sens. Actuators B **91**, 266 (2003).
5. S. D. Soelberg, T. Chinowsky, G. Geiss, C. B. Spinelli, R. Stevens, S. Near, P. Kauffman, S. Yee, and C. E. Furlong, J. Ind. Microbiol. Biotechnol. **32**, 669 (2005).
6. S. J. Kim, K. V. Gobi, R. Harada, D. R. Shankaran, and N. Miura, Sens. Actuators B **115**, 349 (2006).
7. M. E. Stewart, C. R. Anderton, L. B. Thompson, J. Maria, S. K. Gray, J. A. Rogers, and R. G. Nuzzo, Chem. Rev. (Washington, D.C.) **108**, 494 (2008).
8. J. N. Anker, W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, and R. P. Van Duyne, Nature Mater. **7**, 442 (2008).
9. M. E. Stewart, N. H. Mack, V. Malyarchuk, J. A. N. Soares, T. W. Lee, S. K. Gray, R. G. Nuzzo, and J. A. Rogers, Proc. Natl. Acad. Sci. USA **103**, 17143 (2006).
10. J. C. Yang, J. Ji, J. M. Hogel, and D. N. Larson, Nano Lett. **8**, 2718 (2008).
11. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature **391**, 667 (1998).
12. H. A. Bethe, Phys. Rev. **66**, 163 (1944).
13. J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
14. Q. Gan, B. Guo, G. Song, L. Chen, Z. Fu, Y. Ding, and F. Bartoli, Appl. Phys. Lett. **90**, 161103 (2007).
15. Q. Gan, Z. Fu, Y. Ding, and F. Bartoli, Phys. Rev. Lett. **100**, 256803 (2008).
16. Q. Gan, Y. J. Ding, and F. J. Bartoli, Phys. Rev. Lett. **102**, 056801 (2009).
17. S. Lal, S. Link, and N. J. Halas, Nat. Photonics **1**, 641 (2007).
18. L. Nicu and T. Leichle, J. Appl. Phys. **104**, 111101 (2008).
19. J. Homola and M. Piliarik, in *Surface Plasmon Resonance (SPR) Sensors*, Springer Series in Chemical Sensors and Biosensors (Springer, 2006), Vol. 4, p. 45.
20. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, 1985), Vol. 1.
21. K. A. Tetz, L. Pang, and Y. Fainman, Opt. Lett. **31**, 1528 (2006).
22. A. Lesuffleur, H. Im, N. C. Lindquist, and S. H. Oh, Appl. Phys. Lett. **90**, 243110 (2007).
23. A. G. Brolo, R. Gordon, B. Leathem, and K. L. Kavanagh, Langmuir **20**, 4813 (2004).
24. A. D. Leebeek, L. K. Swaroop Kumar, V. Lange, D. Sinton, R. Gordon, and A. G. Brolo, Anal. Chem. **79**, 4094 (2007).
25. J. C. Sharpe, J. S. Mitchell, L. Lin, N. Sedoglavich, and R. J. Blaikie, Anal. Chem. **80**, 2244 (2008).
26. G. M. Hwang, L. Pang, E. H. Mullen, and Y. Fainman, IEEE Sens. J. **8**, 2074 (2008).
27. W. Srituravanich, L. Pan, Y. Wang, C. Sun, D. B. Bogy, and X. Zhang, Nat. Nanotechnol. **3**, 733 (2008).
28. M. Madou, J. Zoval, G. Jia, H. Kido, J. Kim, and N. Kim, Annu. Rev. Biomed. Eng. **8**, 601 (2006).