Colloidal nanophotonics: the emerging technology platform

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Abstract: Dating back to decades or even centuries ago, colloidal nanophotonics during the last ten years rapidly extends towards light emitting devices, lasers, sensors and photonic circuitry to manifest itself as an emerging technology platform rather than an entirely academic research field.

OCIS codes: (160.2540) Fluorescent and luminescent materials; (040.5350) Photovoltaic; (140.0140) Lasers and laser optics; (160.4236) Nanomaterials; (280.4788) Optical sensing and sensors; (140.3460) Lasers; (230.3670) Light-emitting diodes; (250.5403) Plasmonics; (130.6010) Sensors; (140.3945) Microcavities; (050.5298) Photonic crystals

References and links

1. C. J. Reckmeier, J. Schneider, A. S. Susha, and A. L. Rogach, "Luminescent colloidal carbon dots: optical properties and effects of doping," Opt. Express **24**(2), A312–A340 (2016).
2. S. Gonzalez-Carrero, R. E. Galian, and J. Perez-Prieto, "Organic-inorganic and all-inorganic lead halide nanoparticles," Opt. Express **24**(2), A285–A301 (2016).
3. T. Erdem, Z. Soran-Erdem, Y. Kelestemur, N. Gaponik, and H. V. Demir, "Excitonic improvement of colloidal nanocrystals in salt powder matrix for quality lighting and color enrichment," Opt. Express **24**(2), A74–A84 (2016).
4. J. Pan, J. Chen, D. Zhao, Q. Huang, Q. Khan, X. Liu, Z. Tao, Z. Zhang, and W. Lei, "Surface plasmon-enhanced quantum dot light-emitting diodes by incorporating gold nanoparticles," Opt. Express **24**(2), A33–A43 (2016).
5. L. J. McLellan, B. Guilhabert, N. Laurand, and M. D. Dawson, "CdS_xSe_{1-x}/ZnS semiconductor nanocrystal laser with sub 10kW/cm^2 threshold and 40nJ emission output at 600 nm," Opt. Express **24**(2), A146–A153 (2016).
6. W. Xie, Y. Zhu, T. Aubert, Z. Hens, E. Brainis, and D. Van Thourhout, "Fabrication and characterization of on-chip silicon nitride microdisk integrated with colloidal quantum dots," Opt. Express **24**(2), A114–A122 (2016).
7. D. Melnikau, D. Savateeva, N. Gaponik, A. O. Govorov, and Y. P. Rakovich, "Chiroptical activity in colloidal quantum dots coated with achiral ligands," Opt. Express **24**(2), A65–A73 (2016).
8. E. V. Ushakova, S. A. Cherevkov, A. P. Litvin, P. S. Parfenov, V. V. Zakharov, A. Dubavik, A. V. Fedorov, and A. V. Baranov, "Optical properties of ordered superstructures formed from cadmium and lead chalcogenide colloidal nanocrystals," Opt. Express **24**(2), A58–A64 (2016).
9. D. U. Lee, D. H. Kim, D. H. Choi, S. W. Kim, H. S. Lee, K.-H. Yoo, and T. W. Kim, "Microstructural and optical properties of CdSe/CdS/ZnS core-shell-shell quantum dots," Opt. Express **24**(2), A350–A357 (2016).
10. N. V. Tepliakov, M. Yu. Leonov, A. V. Baranov, A. V. Fedorov, and I. D. Rukhlenko, "Quantum theory of electroabsorption in semiconductor nanocrystals," Opt. Express **24**(2), A52–A57 (2016).
11. O. S. Kulakovich, E. V. Shabunya-Klyachkovskaya, A. S. Matsukovich, K. Rasool, Kh. A. Mahmoud, and S. V. Gaponenko, "Nanoplasmonic Raman detection of bromate in water," Opt. Express **24**(2), A174–A179 (2016).
12. G. Perozziello, P. Candeloro, A. De Grazia, F. Esposito, M. Allione, M. L. Coluccio, R. Tallerico, I. Valpapuram, L. Tirinato, G. Das, A. Giugni, B. Torre, P. Veltri, U. Kruhne, G. D. Valle, and E. Di Fabrizio, "Microfluidic device for continuous single cells analysis via Raman spectroscopy enhanced by integrated plasmonic nanodimers," Opt. Express **24**(2), A180–A190 (2016).
13. A. Muravitskaya, A. Rumyantseva, S. Kostcheev, V. Dzhagan, O. Stroyuk, and P.-M. Adam, "Enhanced Raman scattering of ZnO nanocrystals in the vicinity of gold and silver nanostructured surfaces," Opt. Express **24**(2), A168–A173 (2016).

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14. E. V. García-Ramírez, S. Almaguer-Valenzuela, O. Sánchez-Dena, O. Baldovino-Pantaleón, and J. A. Reyes-Esqueda, "Third-order nonlinear optical properties of colloidal Au nanorods systems: saturable and reverse-saturable absorption," Opt. Express **24**(2), A154–A167 (2016).
15. Z. Xiong, T. Wei, Y. Zhang, J. Wang, and J. Li, "Multiple-exposure colloidal lithography for enhancing light output of GaN-based light-emitting diodes by patterning Ni/Au electrodes," Opt. Express **24**(2), A44–A51 (2016).
16. J.-H. Min, X. A. Zhang, and C.-H. Chang, "Designing unit cell in three-dimensional periodic nanostructures using colloidal lithography," Opt. Express **24**(2), A276–A284 (2016).
17. Ö. Sepsi, S. Pothorszky, T. M. Nguyen, D. Zámbó, F. Ujhelyi, S. Lenk, P. Koppa, and A. Deák, "Preparation and characterization of two dimensional metallic nanoparticle and void films derived from a colloidal template layer," Opt. Express **24**(2), A424–A429 (2016).
18. C. Trompoukis, I. Massiot, V. Depauw, O. E. Daif, K. Lee, A. Dmitriev, I. Gordon, R. Mertens, and J. Poortmans, "Disordered nanostructures by hole-mask colloidal lithography for advanced light trapping in silicon solar cells," Opt. Express **24**(2), A191–A201 (2016).
19. W. Z. W. Ismail, G. Liu, K. Zhang, E. M. Goldys, and J. M. Dawes, "Dopamine sensing and measurement using threshold and spectral measurements in random lasers," Opt. Express **24**(2), A85–A91 (2016).
20. V. Yu. Reshetnyak, I. P. Pinkevych, T. J. Sluckin, and D. R. Evans, "Cloaking by shells with radially inhomogeneous anisotropic permittivity," Opt. Express **24**(2), A21–A32 (2016).
21. B. Wang, Q. Zhan, Y. Zhao, R. Wu, J. Liu, and S. He, "Visible-to-visible four-photon ultrahigh resolution microscopic imaging with 730-nm diode laser excited nanocrystals," Opt. Express **24**(2), A302–A311 (2016).
22. N. V. Kamanina, Yu. A. Zubtcova, A. A. Kukharchik, C. Lazar, and I. Rau, "Control of the IR-spectral shift via modification of the surface relief between the liquid crystal matrixes doped with the lanthanide nanoparticles and the solid substrate," Opt. Express **24**(2), A270–A275 (2016).
23. R. W. L. van Vliembergen, L. J. van Ijzendoorn, and M. W. J. Prins, "Distance within colloidal dimers probed by rotation-induced oscillations of scattered light," Opt. Express **24**(2), A123–A138 (2016).

This feature issue is designed to provide recent highlights in the fast and vast field of modern nanoscience which tends to become a new well defined technological platform, namely colloidal nanophotonics. It actually dates back to ancient times as real nanotechnology applied to color glass in cups, stained-glasses, and pottery, as the dawn of nanoscience recalling first experiments by Michael Faraday on optical properties of gold colloidal solutions in 1857, then as commercial cut-off semiconductor-doped glass filters many decades ago. Further prerequisites can be found in early predictions of inhibited spontaneous emission of light in periodic structures (V. P. Bykov, 1972), in the first experiments on enhanced light-matter interaction with metal colloidal nanoparticles by M. Kerker et al. (1980), and in size-dependent properties of metal particle suspensions. Nowadays there are three major fields which constitute colloidal nanophotonics, namely

(i) quantum confinement effects on emission and absorption of light by *semiconductor* nanocrystals (quantum dots) pioneered by Alexei Ekimov, Alexander Efros, and Louis Brus in 1980s,

(ii) photon, or more accurately, light waves confinement phenomena in colloidal *dielectric* microstructures (microcavities and photonic crystals),

(iii) colloidal nanoplasmonics, i.e. a variety of phenomena related to light-matter interaction in *metal*-dielectric colloidal nanostructures.

Semiconductor nanocrystals often referred to as quantum dots do form the core of colloidal nanophotonics since these offer size-controlled light emission including light-emitting diodes and lasing. Light-wave confinement phenomena in dielectric and metal colloidal structures can be used to develop passive filters or to enhance light-matter interaction in active species like semiconductor quantum dots, atoms, and molecules. These structures offer multiple applications from various sensors to photonic circuitry via light modes confinement and coupling. Not only photon management on a nanoscale can be performed with colloidal structures but also novel mesoscopic structures and hybrid materials structures for photonics and beyond can be fabricated using colloidal lithography and self-assembly. All above trends of colloidal nanophotonics are presented in this feature issue.

Electronic confinement effects play the dominant role in colloidal nanophotonics and thanks to efforts of many groups over the world, the first commercial applications of quantum dot emitters in display devices has become recently possible. A number of papers in this issue are related to colloidal quantum dots photophysics and applications. C. J.

Reckmeier et al. [1] provide a review on recent progress in synthesis of colloidal carbon dots and discuss their luminescent properties. S. Gonzalez-Carrero et al. [2] highlight advances on fabrication and characterization of a new class of semiconductor quantum dots, namely perovskite nanocrystals of lead halides. T. Erdem with associates [3] discuss possible ways to improve by means of salt powder matrix quantum dot based luminophores for lighting. Several research groups contributed with the works on improvement of quantum dot based devices. J. Pan et al. [4] managed to enhance colloidal quantum dot LED output by means of nanoplasmonics using gold nanoparticles. L. J. McLellan et al. [5] report on nanocrystalline laser for red spectral range. W. Xie et al. [6] experimentally realized on-chip coupling of colloidal quantum dots to silicon nitride microdisks. Several teams provided recent advances in fabrication and characterization of novel colloidal quantum dot structures. D. Melnikau et al. [7] have developed an approach towards chiral optical activity of nanocrystals using ligands. E. Ushakova et al. [8] developed ordered colloidal nanocrystalline superstructures from cadmium and lead chalcogenide that may have further applications in photodetectors and solar cells. D.U. Lee et al. [9] synthesized three-component core-shell-shell onion-like nanocrystals. Last but not least in the subsection of works is the report by N. Teplyakov et al. [10] on the theory of electroabsorption for semiconductor nanocrystals of various topologies. This approach, though not being exhaustive because it implies infinite barriers, which is not often the case in colloidal nanostructures, is meaningful since it can provide a plausible explanation to recently reported electroabsorptive behavior of nanoplatelets versus dots.

Nanoplasmonics in this Issue is presented dominantly by applications of metal-enhanced Raman scattering to sensing. This field though being examined for decades has not yet resulted in any commercial device based on plasmonically enhanced Raman scattering. The issues here are (i) selective enhancement of Raman signatures from the molecules in question to ensure higher signal-to-noise ratio, (ii) high reproducibility of the nanotopology of surface, (iii) and possible application of markers for tracing target molecules instead of analyzing Raman signals from the molecules themselves. Three groups of authors in this Issue reveal and examine different aspects of the problem. O.S.Kulakovich with associates [11] suggests an approach to bromate detection in desalinated water by using plasmonically enhanced Raman scattering to monitor Rhodamine 6G catalytic oxidation by bromate. G. Perozziello with co-workes [12] demonstrate efficient molecular sensing with plasmonic dimers. Recently plasmonic enhancement of Raman scattering has been demonstrated for semiconductor nanocrystals, and colloidal quantum dots when conjugated with biomolecules have been suggested as Raman markers to trace biomedical phenomena instead of fluorescent markers. The work by A. Muravitskaya et al. [13] contributes to this trend by studying plasmonic effects on Raman scattering by ZnO nanocrystals. E. V. García-Ramírez et al. [14] report on plasmonic research beyond sensors, namely, non-linear optical phenomena for gold nanorods interacting with intense laser light.

A noticeable portion of contributed works is related to **colloidal lithography** as cheap and affordable technique providing fabrication of submicron nanorelief without traditional nanolithographical templating. Z. Xiong et al. [15] applied colloidal lithography to patterning of metal electrodes in GaN-based LEDs to enhance light extraction. J.-H. Min et al. [16] demonstrate a way to develop 3D-periodic structure by using lithography with a 2D-periodic colloidal array. To develop highly reproducible nanotextured metal surfaces for plasmonic nanosensors, Ö. Sepsi et al. [17] suggest two dimensional metallic nanoparticle and void films derived from a colloidal template layer. To enhance silicon solar cells performance, C. Trompoukis et al. [18] demonstrate disordered nanostructures developed by hole-mask colloidal lithography for efficient light trapping.

A number of contributions, as is always the case in every new field, can be classified as interdisciplinary studies. A smart approach to dopamine sensing has been suggested by W. Z. W. Ismail et al. [19] using impact of dopamine admixture to the threshold of colloidal random laser. V. Reshetnyak et al. [20] examine theoretically the cloaking phenomenon by shells with radially inhomogeneous anisotropic permittivity. B. Wang et al. [21] demonstrate ultrahigh resolution imaging through multi-photon effects. N. Kamanina et al.

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[22] examine the effect of lanthanide nanoparticles on liquid crystal structures, and R. W. L. van Vliembergen et al. [23] suggest a technique of fine distance monitoring between colloidal nanoparticles in dimers.

The dominance of experimental studies as compared to theoretical ones, which address practical devices issues like luminophores, light emitters, lasers, sensors, light trapping, light extraction confirm the transition of colloidal nanophotonics from an academic research to an emerging technological platform to promise versatile, cheap, environmentally friendly and technologically flexible industrial implementations.

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