Slow-light enhancement of Beer-Lambert-Bouguer absorption

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Optical techniques are finding widespread use in chemical and biochemical analysis, and Beer-Lambert-Bouguer (BLB) absorption, in particular, has become one of the classical workhorses in analytical chemistry. During the past decade, there has been an increasing emphasis on miniaturization of chemical analysis systems and naturally this has stimulated a large effort in integrating microfluidics and optics in lab-on-a-chip microsystems, partly defining the emerging field of optofluidics. At the same time, there is an increasing attention to slow-light phenomena as well as the fundamentals and applications of light-matter interactions in electromagnetically strongly dispersive environments.

In this letter we consider the classical problem of BLB absorption. As with the phenomenon of photonic band-edge lasing, we show how slow light in an optofluidic environment facilitates enhanced light-matter interactions, by orders of magnitude. The proposed concept provides strong opportunities for improving existing miniaturized chemical absorbance cells for Beer-Lambert-Bouguer absorption measurements widely employed in analytical chemistry. © 2007 American Institute of Physics. [DOI: 10.1063/1.2720270]

Slow-light enhancement of Beer-Lambert-Bouguer absorption
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The authors theoretically show how slow light in an optofluidic environment facilitates enhanced light-matter interactions, by orders of magnitude. The proposed concept provides strong opportunities for improving existing miniaturized chemical absorbance cells for Beer-Lambert-Bouguer absorption measurements widely employed in analytical chemistry.

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FIG. 1. (Color online) Schematic of (a) classical setup of Beer-Lambert-Bouguer chemical absorbance cell and [(b)-(d)] examples of strongly dispersive environments provided by photonic crystals with dielectric regions (grey) with a dielectric function different from that of the liquid sample (blue).
Compared to the bare liquid such a composite medium may support an enhancement of the effective absorption. The enhancement factor $\gamma = \alpha/\alpha_l$ can now be expressed as

$$\gamma = f \times \frac{c n_l}{v_g}, \quad f = \frac{\langle E|D|\rangle}{\langle E|D\rangle},$$

where we have introduced the displacement field $|D| = \varepsilon |E|$. The integral in the numerator of the filling factor $0 < f < 1$ is restricted to the region containing the absorbing fluid while the integral in the denominator is spatially unrestricted. This expression clearly demonstrates how BLB absorption benefits from slow-light phenomena. For liquid infiltrated photonic crystals and photonic crystal waveguides, it is possible to achieve $v_g \ll c$ and at the same time have a filling factor of the order unity, $f \sim 1$, whereby significant enhancement factors become feasible. The effective enhancement of the absorption can also be understood in terms of an effective enhancement of the light-matter interaction time given by the Wigner-Smith delay time $\tau$. For the homogeneous problem, we have $\tau \sim L/(c n_l)$ while for the strongly dispersive problem $\tau \sim L/v_g$ so that $\gamma \sim \tau L/(c n_l) v_g$ in agreement with the result in Eq. (2) rigorously derived from perturbation theory. The presence of the filling factor $f$ is also easily understood since only the fraction $f$ of the light residing in the fluid can be subject to absorption. These conclusions may also be extended to nonperiodic systems, including enhanced absorption in disordered systems as well as intracavity absorbance configurations, by use of scattering matrix arguments.

Let us next illustrate the slow-light enhancement for the simplest possible structure: a Bragg stack with normal incidence of electromagnetic radiation. Panel (a) of Fig. 2 shows the photonic band structure of an optofluidic Bragg stack of period $\Lambda = a_1 + a_2$ with the low-index material layers of width $a_1 = 0.8\Lambda$ being a liquid with refractive index $n_1 = 1.3$, while the high-index layers have a width $a_2 = 0.2\Lambda$ and a refractive index $n_2 = 3$. Photonic band gaps are indicated by yellow shading and the dashed line indicates the long-wavelength asymptotic limit with $\omega = c k \Lambda/(a_1 n_1 + a_2 n_2)$. When approaching the band-gap edges, the dispersion flattens corresponding to a slow group velocity. It is well known that the flat dispersion originates from a spatial localization of the field onto the high-index layers and thus $f \ll 1$ near the band edges where the inverse group velocity diverges. However, in spite of the localization, the enhancement factor may still exceed unity as shown in panel (b) where the dashed line indicates the long-wavelength asymptotic limit with $\gamma = \omega_0 c k L/(a_1 n_1 + a_2 n_2)$. In order to further benefit from the slow-light enhanced light-matter interaction, we obviously have to pursue optofluidic structures supporting both low group velocity and at the same time large filling factors. Figure 3 shows one such example where high-index dielectric rods are arranged in a square lattice. Compared to the Bragg stack, some of the modes in this structure have both a low group velocity and at the same time a reasonable value of the filling factor $f$. Particularly the third band in panel (a) is quite flat and with a finite $f$ giving rise to an enhancement factor $\gamma$ exceeding 5 even at the center of the band. As indicated on the right $y$ axis, the enhancement may have a bandwidth of order of 50 nm for a pitch around $\Lambda \sim 850$ nm, which indeed makes fabrication of such structures realistic with state of the art micro- and nanofabrication facilities. As a final example, Fig. 4 shows the result of introducing a line-defect waveguide in such a structure. The waveguide mode has $f \sim 60\%$ combined with a low group velocity near the band edges.
For the one-dimensional problem in Fig. 2 and 210 absorbance cells. Previous work on liquid-infiltrated photonic crystals to enhance Beer-Lambert-Bouguer absorption. The slow-light enhancement of the absorption, by possibly orders of magnitude, may be traded for yet smaller miniaturized systems or for increased sensitivity of existing devices.

In conclusion, we have studied the potential of using liquid-infiltrated photonic crystals to enhance Beer-Lambert-Bouguer absorption. The slow-light enhancement of the absorption, by possibly orders of magnitude, may be traded for yet smaller miniaturized systems or for increased sensitivity of existing devices.

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