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A novel technique based on Bloch surface waves sustained by one-dimensional photonic crystals to probe mass transport in a microfluidic channel

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ABSTRACT

We report on the use of an optical sensing platform based on Bloch surface waves sustained by one-dimensional photonic crystals as a novel optical tool to probe in real time the fluid flow at a boundary wall of a microfluidic channel under dynamic conditions. Understanding how fluid flow interacts with wall surfaces is crucial for a broad range of biological processes and engineering applications, such as surface wave biosensing. The proposed platform provides nanometric resolution with respect to the distance from the boundary wall sensor's surface. Here, for the first time, we report on the experimental investigation on the temporal evolution of the interface between two fluids with different refractive indices under convective and diffusive conditions. The temporal evolution of the fluids interface in proximity of the wall is recovered. From the data analysis, the diffusion coefficients of glucose and glycerol in water are measured and found in good agreement with the literature. Tuning the one-dimensional photonic crystals geometry and the Bloch surface wave's dispersion has the potential to probe the fluid flow in an extremely wide range of distances from the microfluidic channel wall.

1. Introduction

During the past decade, a wide range of protein microarray technologies have been developed promoting rapid progress in the fields of experimental and clinical investigations [1,2] and an increasing demand of non-invasive sensing makes surface waves as one of the most useful detection techniques. Microfluidics and the design of micro-total analysis systems (μ-TAS) are the most promising aspects to address the inherent complexity of biological systems with massive experimental parallelization and measurements of protein–protein, cell–protein and inter cellular interactions in real-time [3–5].

Most of such sensing schemes exploit the properties of surface plasmon polaritons (SPP) sustained at a metal/dielectric interface and related phenomena, such as long range and localized SPP [6,7]. Among all applications, SPP were also proposed by Loureiro et al. to monitor the mass transport features in proximity of a sensor's surface [8]. The evanescent field can indeed be used as a nanoscopic probe of the external fluid and locally investigate its properties at the micro/nanoscale, which can be extremely different compared to the macro-scale [9].

In this work, we propose a new integrated optical approach to effectively monitor the mass transport features exploiting the properties of another type of electromagnetic surface waves, which can be excited at the interface between a fully-dielectric one dimensional photonic crystal (1DPC) and an external liquid medium [10]. These are commonly referred to as Bloch surface waves (BSW) and have attracted much interest during the last few years. Since 1DPC are dielectric structures, compared to SPP, BSW present very low absorption, long propagation lengths, operate both in the TE and TM polarization, can be excited at any wavelength and do not suffer from metal quenching in fluorescence based schemes [11]. They were proposed for biosensing applications [11], early cancer biomarkers detection [12–14], enhancement of the Goos–Hanchen shift [15], surface-enhanced Raman scattering [16], room temperature polaritons [17], integrated optics [18].

The main goal of the present work is to make use of a phase-sensitive sensor based on BSW to evaluate the diffusion char-

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acteristics of a solute in an aqueous solution under dynamic flow conditions in the proximity of the 1DPC surface. For the particular 1DPC reported here, the intensity of the evanescent tail of the BSW decreases within the fluid with a decay length, d, that is of the order of 110 nm; therefore, the system is able to detect refractive index variations in a small laminar volume very close to the sensor surface. By injecting into a microfluidic channel solutions with different solute concentrations, that means different refractive indices, one can follow in real time the changes of the BSW features for a variety of different experimental conditions. From such investigations, we can address the transport of solutes in aqueous solutions in both convective and diffusive regimes.

The proposed approach could meet an important need in microfluidic technologies, which create devices useful in fields from medical testing to toxin detection [19]. It could be particularly important for miniaturized devices that rely on volume measurements to report, for example, the concentration of a particular molecule in a mixture or characterize in terms of diffusion of such molecules in a biological environment [20].

2. Optofluidic detection technique

2.1. BSW sustained by 1DPC

1DPCs are periodic multilayer stacks with an elementary unit formed by two dielectric layers with a high refractive index mismatch [10,21]. The optical properties of an infinite 1DPC are characterized by permitted TE and TM photonic bands, separated by photonic bandgaps (PBG) [10]. When the periodicity is abruptly interrupted, BSWs modes may appear in the PBG and light can be localized at the 1DPC surface [10,22,23]. Additionally, surface defect layers that make the 1DPC non-periodic can be used to further tailor the BSW dispersion. The BSW field envelope decays exponentially in the 1DPC and in the homogeneous external medium due to Bragg reflection and total internal reflection (TIR), respectively [10,24].

In the present case, BSW are guided at the interface between a finite 1DPC deposited on a glass microscope slide and a homogeneous external liquid. In a, we show the calculated BSW intensity profile as a function of the optical distance from the surface, normalized to the operation wavelength y_{opt}/λ. The numerical simulations were carried out by means of the transfer matrix method (TMM) [10,25]. For the specific 1DPC used in the present work, the BSW decay length in the external medium d (geometric), where the intensity is attenuated by 1/e with respect to the surface, is found for $y_{opt}/\lambda = 0.224$ (see dashed lines in Fig. 1a and is $d = y_{opt}/n_L = 0.224 \times \lambda/n_L$, where n_L is the refractive index of the external medium.

Fig. 1a shows a very important feature of BSW; if one scales the wavelength λ and the optical thicknesses of the 1DPC layers by the same factor the plot does not change. This allows to tune the decay length $d = 0.224 \times \lambda/n_L(\lambda)$ and probe the external fluid in a thinner/thicker layer close to the surface. As examples, for the 1DPC shown in Fig. 1a, one would get d = 67nm for λ = 405 nm (InGaN laser) and d = 263 nm for λ = 1550 nm (InGaAsP laser). Of course, such feature relies on the availability of transparent dielectrics for the 1DPC layers at the scaled wavelength, which can be easily found. An even larger range of variation of d can be achieved if one completely changes the 1DPC (and illumination angle), not only scaling it, even keeping λ fixed [26]. Such a tuning feature is not provided by SPP which can operate only in a restricted range of wavelengths, depending on the specific conducting material used [27].

From a practical point of view, the BSW at the given wavelength λ is obtained by prism coupling in the so called Kretschmann–Raether configuration [25,28]. The microscope slide with the deposited 1DPC is coupled to a BK7 prism by means of an index-matching oil and topped by a fluidic cell, as shown in Fig. 1b. The fluid flow at the interface with the 1DPC is guaranteed by the holes of inlet and outlet. In TIR conditions, the BSW at the resonance angle, θ_{RES}, is revealed in the angular reflectance spectrum with a dip very narrow if compared with the surface plasmon polaritons (SPP), as shown in Fig. 1c. The resonance angular position depends by the optical properties of the external medium and perturbations at the surface can be observed and quantified by tracking its angular position.

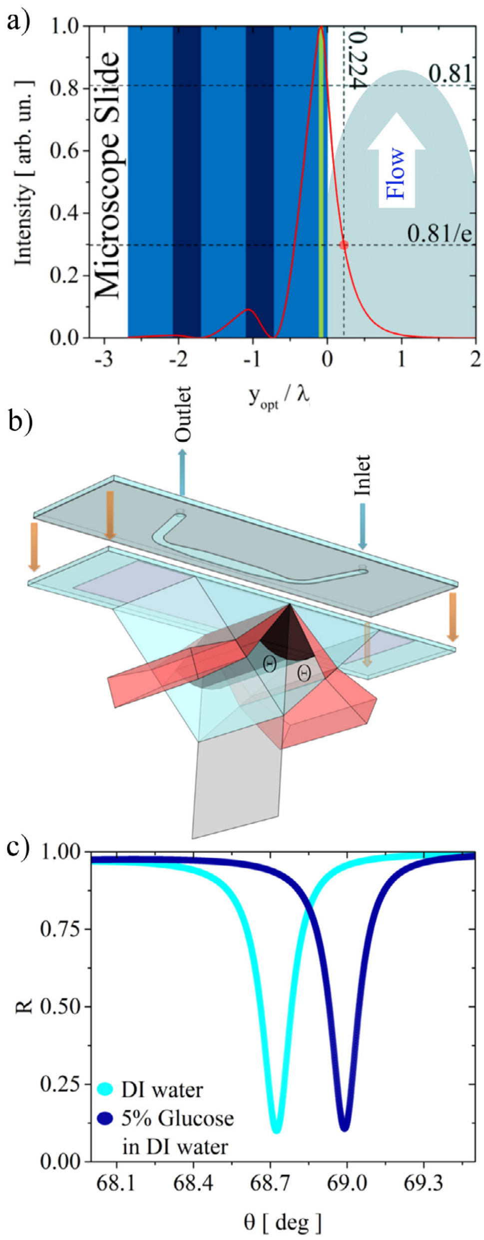

Fig. 1. (a) BSW transverse intensity profile calculated at resonant excitation in DI water; the intensity is plotted as a function of the optical distance from the 1DPC surface normalized to λ. (b) Sketch of the BSW excitation scheme making use of a prism coupler in the Kretschmann–Raether configuration and operating under TIR conditions. (c) TMM calculated reflectance for DI water and 5 wt% glucose solutions ($\Delta n = -7.35 \times 10^{-3}$ RIU).

2.2. 1DPC optical transducer

The 1DPCs utilized in this work were fabricated by plasma ion assisted electron beam evaporation under high vacuum conditions