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Polymer resonators sensors for detection of sphingolipid gel/fluid phase transition and melting temperature measurement

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ABSTRACT

This work describes a low-cost biophotonic sensor shaped by way of cheap processes as hybrid silicon/silica/polymer resonators able to detect biological molecule gel/fluid phase transition as lipids at very low concentration (sphingomyelin). The photonic structure is composed of specific amplified deep UV photoresist-polymer waveguides coupled by a sub-wavelength gap with racetrack microresonators allowing a low temperature-dependent operation ranging from 16 to 42 °C. The temperature dependent wavelength shift and the thermo-optic coefficient characterizing the quantified resonances and opto-geometric properties of the device have been evaluated, highlighting an enough low thermal features of the whole system for such application. With an appropriate vesicle lipid deposition process specific in biology associated to an apt experimental bio-thermo-photonic protocol (made of serial optical resonance spectra acquisitions with statistical treatments), the dynamic evolution of the sphingomyelin lipid phase transition was assessed: then, the ability to detect their own gel/fluid transition phase and melting temperature has been demonstrated with a mass product factor 10^7 lower than that of more conventional methods The equilibrium of the regime of the resonators was highlighted as being broken by the dynamic of the sphingomyelin and its own phase transition prior relevant detection.

1. Introduction

Optical microcavities or microresonators have been most generic components, for the last decade, so as to design and fabricate integrated photonic devices leading to the development of numerous applications in science. They include as much fundamental physics studies as the researches for engineering telecommunications, biophysics, biochemical and biology [1–3]. Indeed, optical microcavities are quite welcome devices allowing to control optical fields as regards their spatial localization and very lifetime. To a certain extent, as such resonant quantifications met in physics are due to a geometric recirculation of the light (called whispering gallery modes – WGMs), they increase both the field and merit of integrated photonics regarding a significant set of optical telecommunications versatile applications (including filters, switches, modulators, de/multiplexing components, lasers...) together with sensors for metrology with platform analysis and relevant detection procedure. The spatial localization of the light, due to the fundamental optical laws and the nature of the evanescent part of the light which is not completely confined, acts as a tunable probe for the surrounding and enables the light to interact and feel the environment. For example, considering the recent development of telecommunication components, specific low thermal properties have been widely searched so as to obtain a response function or a signal transduction of operative devices as much as possible independent in temperature [4]. Such significant and crucial properties allow a striking improvement of the components operating range with enhanced stability in strong environmental conditions. Regarding sensors applications requiring such driftless properties, the response signal of ideal components should be quasi temperature independent, allowing then output signals only depending on the samples to be detected. Sundry approaches and processes have been developed on successive classes of materials in order to shape, on 2D planar technologies or 3D hybrid con-

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figurations, different architectures of microresonators (ring, disk, stadium, racetrack, toroid, cylinder, sphere and so on) [5–9]. In an overall landscape of technologies, resonators based on organic materials exhibit a lot of advantages due to the well-established printing or photolithographic technologies, the versatility of the polymer properties and functionalization and the possibility to be shaped starting from a liquid photoresist material with fluidic thin layer specific deposition principles [9–13]. All these are reproducible ways and concepts. Globally, the reasons of the progress in this research field are various and easily justified with the potential of numerous available materials, the simplicity of the relevant processes, the specific methods and measurements protocols and low costs of the entailed devices. Furthermore, together with designs immune against temperature changes, one can expect the ability to detect a specific function for sensors applications, an apt recycling or the possibility of further uses of the components in biodetection after simple water washing, the stability of the optical response functions and so on. More recently, after the substantial development in telecommunications, organic materials based resonators have received intensive attention in metrology and sensing environmental applications, biology, medical and healthcare diagnostics, food quality control and security. Such photonics sensors relying on resonators have become the subject of comprehensive research with sizeable developments of enhanced sensing platforms devoted to the label-free detection of a wide variety of chemical and biochemical [14–18], biological agents and biomedical materials [19–28].

Sphingomyelin (SPH) is a type of sphingolipid that can also be classified as sphingophospholipids, found in animal cell membranes. SPH is especially prominent in myelin, a membranous sheath that surrounds and insulates the axons of numerous neurons [29–32]. In humans, SPH represents 85% of all sphingolipids, and typically make up 10–20 mol% of plasma membrane lipids with higher concentrations found in nerve tissues, red blood cells, and the ocular lenses... Such a plasma membrane component participates in many signaling pathways. The metabolism of SPH creates many products that play significant roles in the cell. As an example SPH undergoes significant interactions with cholesterol. The latter has the ability to strongly shift the liquid to solid phase transition in phospholipids. Since sphingomyelin transition temperature stands within physiological temperature ranges, cholesterol can play a significant role in the phase of sphingomyelin.

The present work is aimed at exploring and investigating low-cost and easily reproducible polymeric biophotonic sensors integrated on a chip-device which features an enough low thermal behavior so as to detect SPH phase transition. They are devoted to perform efficient sphingomyelin lipid first order phase transition detection based on a gel-liquid state-change and then melting temperature determination. The lipids used, here, is the sphingomyelin (SPH), which plays a crucial role in the biology and the biochemical aspect in the particular function of plasma membrane of cells. The first section describes the global fabrication involving thin layer processes, starting from the chemical and materials aspects to achieve suitable deposition of biological samples, which are relevant in our compound approach. This comprises the use of attractive organic amplified photoresins with specific deep UV technology associated with an appropriate lipid deposition process related to biology. In addition, sundry characterization methods regarding the on-chip-device are described so as to validate both its concept and design. Furthermore, we also detail in a second section, the versatile principle of operation and justify the measurements approach together with experiments developed for such a specific biometrology ascribed to temperature dependent lipid phase transition detection. The appropriate bio-thermo-photonic method and protocol, based on serial optical resonance spectra acquisitions and statistical treatments on a sensing platform design, are also depicted. An adequate low thermal feature of the chip device (sensors without lipid deposit) is established: the system is not so sensitive to temperature changes in a wide range from 16 °C to 42 °C and then is appropriate to detect specific molecules localized on the top of the chip so as to assess their relevant biomechanisms. Then in the third and last section, the ability to follow the dynamic evolution of sphingomyelin (SPH) with temperature by detecting their own gel/fluid transition phase can be emphasized, together with the determination of the melting temperature due to changes of the specific parameters accounting for the optical spectra. The ability to detect their own gel/fluid transition phase and melting temperature will be clearly demonstrated with a mass product factor 10^7 lower than that of differential scanning calorimetry method in comparison.

2. Design, materials and processes, realization and characterization of the structure

2.1. Theory on opto-geometric considerations concerning the optical single-mode behavior

So as to operate on quasi-TE_{00} and -TM_{00} single-mode eigenvectors, adequate and straightforward simulations have been previously achieved considering the theory of electromagnetism in waveguides allowing us to obtain eigenvalues equations: then, all the series of quantified effective propagation constants $\beta = k_0.n_{eff}$ or effective indices n_{eff} can be settled defining then the apt opto-geometric parameters for such photonic structures. These typical dimensions (h-height and w-width) regarding refractive indices enable us to operate with exclusive monomode TE_{00}-TM_{00} optical modes. The methodology supporting such simulations consists in solving the J.C. Maxwell's equations in each part of the whole system while taking into account the continuity properties of the electromagnetic fields so as to obtain the so-called eigenvalues equations that highlight directly the overall quantifications of the fields viewed as eigenvectors. Such photonic structures or opto-geometrical systems show-off an intrinsic asymmetry especially in the optical indices entailing a cut to occur in the dispersion curves of the modes. As an example, considering the first operation of quantification along the direction perpendicular to the wafer surface with regard to the apt electromagnetism theory, it is easy to define the cut-thickness notion regarding both the TE_m and TM_m modes (m integer) within our structure:

$$h_{cut} = \frac{\lambda_0}{2\pi\left(n^2_{DUV210} - n^2_{SiO2}\right)^{1/2}} \left\{ \text{arctg}\left[\eta_{DUV210/upper-cladd}\left(\frac{n^2_{SiO2} - n^2_{upper-cladd}}{n^2_{DUV210} - n^2_{SiO2}}\right)^{1/2}\right] + m\pi \right\}, \quad (1)$$

Here, $n_{material}$ stands for the relevant refractive indices, considering the DUV210 polymer core and respective claddings (lower SiO_2, upper air or lipids) at λ_0-wavelength; also, $\eta_{DUV210/upper-cladd} = 1$ or $\left(\frac{n_{DUV210}}{n_{upper-cladd}}\right)^2$ for their respective TE_m and TM_m polarizations. Below the h_c-values at m = 0, with no eigenvectors allowing the light to occur, a consequent forbidden area is located out of the cone of light; the latter gives rise to the dispersion curves related with the family of bounded or guided modes. Between the ranging of h_c-values (Table 1) corresponding to the cut-thicknesses at respectively [m = 0; m = 1], both TE_0- and TM_0 single-modes occur and propagate with a high probability of presence. In conclusion, a rib waveguide typically 800 nm in thickness × 2 μm DUV210, arranged onto SiO_2/Si (shaped as described previously into the paper) makes certain to maintain a single-mode characteristic: then, the device