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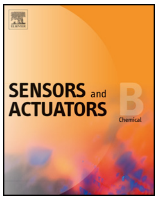

A multispectral resonant waveguide nanopatterned chip for robust oil quality monitoring

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ABSTRACT

Oil quality control is an important issue in the food industry and consumer market. Consequently, on-site control with a user-friendly device at a reasonable cost is needed. Simple optical imaging of resonant peak on a nanostructured chip by a consumer grade camera allows real-time label-free biomolecules sensing and bulk refractive index measurements. Multispectral capability on the same nanostructured chip is introduced for the first time here, both through theory and experiments. We demonstrate that with optimized nanostructuration, the whole visible spectrum can be sensed using the same chip support. By analyzing oil samples from deep frying process, we found cooking process can induce a small ($\sim 10^{-3}$) but stable and detectable change of the refractive due to the accumulation of polar materials. This is measured accurately thanks to the high-sensitivity of our refractive index sensing chip ($\Delta n \sim \pm 1 \times 10^{-5}$). Refractive index change of a mixture of animal fat and vegetable oil is also studied. We compare refractive index change at the 2 extremities of the visible spectrum ($\lambda = 480$ nm and $\lambda = 630$ nm), and confirm and ~2 times larger change for small wavelength. Possible integration of our device with powerful imaging capability in recent popular smartphones is also discussed.

1. Introduction

1.1. Oil refractive index sensing

In food production or safety inspection areas it is foremost important to dispose of reliable and convenient devices for on-site oil quality monitoring of edible oils [1]. Indeed, a long and repeated heating of oil induces a series of degradation reactions, such as oxidation, polymerization and hydrolysis. This results in organoleptic deterioration and a decrease in nutrition value. Many of the degradation products are harmful to health as they cause vitamin destruction, enzyme inhibition, and gastrointestinal irritations and might also cause mutations [2].

For its severity of influence and difficulty of accurate identification, china government even requested public proposals to identify the "gutter oil"—a slang word for resold cooking oil refined from used oil [3].

One common criterion for oil quality is its color. Other determination criteria like total polar material determination, acid value or iodine value, are well established characterizations but they are usually performed in a laboratory environment and are time consuming. Considering the need of on-site analysis and fast response, it is of foremost importance to dispose of reliable and convenient devices for oil quality testing purpose.

We propose here a measurement platform based on high sensitivity refractive index measurement performed by simple imaging of a chip patterned with nanogratings. The nanostructuration is designed such that sensing can be carried out at several wavelengths, but using the same chip support.

Color measurement is a simple indicator of oil quality [4]. It is used in pre or post industrialization for instance with colorimeters such as Lovibond [5]. Nevertheless, it has limited accuracy and might be subject to personal bias. Thus some objective and quantitative criteria are desirable. Additionally, color may be falsified by oil mixtures.

By doing refractive index and absorption sensing of oils, different oils might be differentiated and their quality might be controlled as well. The possibility to discard mixtures mimicking

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a good oil based on color is one of the interesting perspectives of this work.

1.2. *"Peak-tracking chip" technique*

The "Peak-tracking chip" technique is a label-free direct imaging technique, which successfully combines the advantages of resonant waveguide grating (RWG) label-free detection and of direct imaging with minimized demand [6]. RWG have some advantages in term of optimized light-matter interaction with immobilized biomolecules or analyte [7]. Such an optimization can be achieved through detection wavelengths, material refractive indices and geometrical parameters of the chip [8]. RWGs based sensing is realized by measuring the shift of the resonance profile, usually of Fano lineshapes [9]. While this is usually achieved by varying an instrumental parameter (wavelength or angle) [10,11], we recently demonstrated that the intensity profile might be integrated in the chip itself in order to become a spatial image. This allows robust and sensitive sensing with consumer-grade CMOS camera [6,12]. This is a significant advantage in term of cost and simplicity, which are highly desired for biosensing or on-site oil testing. Exploiting bi-dimensionality of the resonant chip nanostructuration, multispectral sensing can also be implemented on the same chip support. This is a significant advantage in comparison to usual RWGs sensing techniques [8,10,11], involving a single grating and therefore a single resonant wavelength domain.

Spatial Fano profiles in direct imaging are achieved by slowly varying a geometrical parameter of the grating on a resonant waveguide chip. The work presented first emphasizes monochromatic imaging and sensing. The chip and detection set-up are illustrated in Fig. 1(A) for monochromatic sensing. Multiple sensing tracks can be placed on the same chip, as illustrated in Fig. 1(B) to perform 2D array sensing [6,13]. Each sensing area consists of a track of M nanogratings micropads, these latter having a smoothly varying geometry (and therefore resonant condition) as schemed in Fig. 1(C). The chip presented here corresponds to monochromatic sensing, with identical tracks (same nanostructuration) placed in an array format.

The technique has 2 types of applications: label-free bioarray imaging and bulk solution refractive index sensing. The nanostructuration is chosen depending on the targeted detection wavelength and index range. Real-time DNA hybridization with high sensitivity has recently been demonstrated through the detection of single nucleotide polymorphism. Details on the biology process and fluidic integration of our technique may be found in [14]. Bulk sensing has been demonstrated with known calibrated solutions at a single wavelength $\lambda = 545$ nm, demonstrating a refractive index span of [1.33–1.48] on a single track with filling factor $f_i = [0.3–0.7]$, and a wavelength $\lambda = 545$ nm [6].

We demonstrate here the potential of our technique for oil refractive index sensing, and more specifically taking benefit of sensitivity and multispectral potential. Our chip-based detection technique is also advantageous in term of device simplicity, low amount of analyte required and fast response.

2. Multispectral sensing

2.1. *Spectrally selective tracks*

Our technique is able to measure refractive index variation down to $\Delta n \sim \pm 1 \times 10^{-5}$, as demonstrated through theory and experiments [13]. Sensitive near resonance detection are usually limited to only one wavelength (as the chip has only one resonant condition) [10,11]. Here, by exploiting the nanopattern parameters, we demonstrate that different wavelengths may be sensed using the same chip. More specifically, we make tracks of grating micropads of different periods, thus targeting a different wavelength domain on a given column. Discrete profile values allowing the essential resonance scan are obtained by slowly varying the groove width (and consequently the filling factor) in the vertical direction along a track.

2.2. *Multispectral chip design*

Electromagnetic properties are calculated using scattering matrix formalism [15,16].

Specifically, to demonstrate that the whole visible spectrum can be sensed using the same chip support, we design tracks with periods $\Lambda_b = 380$ nm for sensing at $\lambda_b \sim 480$ nm, $\Lambda_g = 440$ nm for sensing at $\lambda_g \sim 545$ nm and $\Lambda_r = 520$ nm for sensing at $\lambda_r \sim 630$ nm. Thickness of the layers and etching depth are the same for all tracks, allowing a simpler fabrication process through electron beam lithography patterning. A chip with a set of tracks of different periods is presented in Fig. 2 with (A) side-view and (B) top-view.

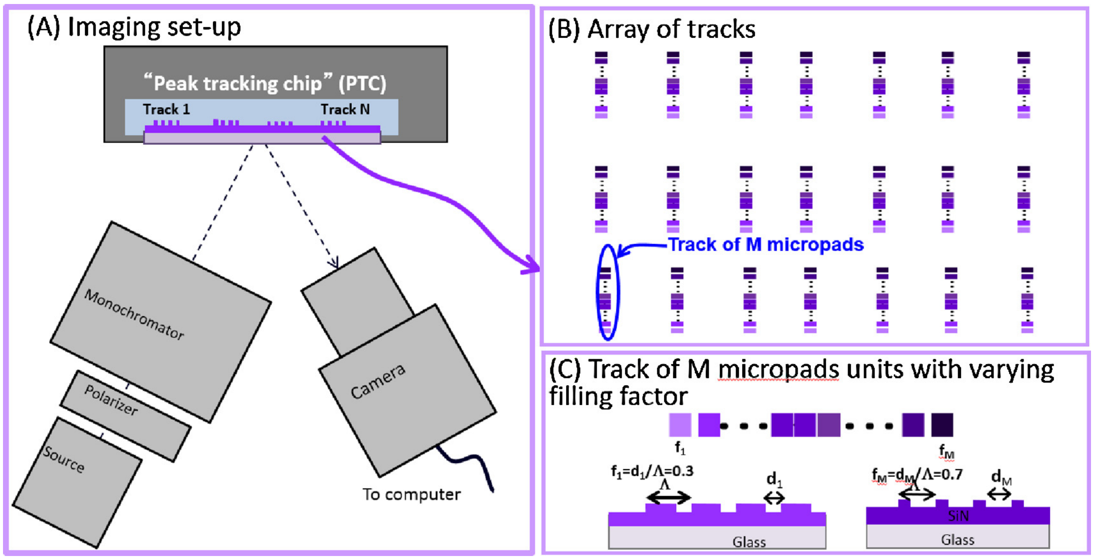

Fig. 1. Technique overview (A) imaging set-up of 2D array nanopatterned chip, (B) array of tracks, (C) track nanostructuration with single period Λ and varying groove with d_i.