A tunable optical filter based on the electrowetting controlled sagging effect of a liquid droplet on a waveguide Bragg grating formed superhydrophobic substrate

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Abstract: A tunable optical filter combining a waveguide Bragg grating and the electrowetting controlled sagging effect of a liquid droplet is proposed. A tuning range above 40 nm with a bandwidth of 0.6 nm is achieved.

OCIS codes: (050.2770) Gratings; (130.7408) Wavelength filtering devices.

1. Introduction

Tunable filters used as wavelength (de)multiplexers in an optical network, functioning as optical switchers and Bragg reflectors in tunable lasers, have recently attracted a great deal of interest among researchers. Filtering configurations including whispering gallery mode (WGM) resonators [1], Mach-Zehnder interferometers [2], fiber Bragg gratings [3], Fabry-Perot microcavities [4], and waveguide Bragg gratings [5] are widely studied. Among them, waveguide Bragg gratings can be facilely integrated with various platforms, such as silicon-on-insulator (SOI), silica planar lightwave circuits (PLC), indium phosphide monolithic and Bloch surface wave (BSW) platforms, and therefore have been extensively investigated.

During the past two decades, electrowetting on dielectric (EWOD) has emerged as an effective liquid droplet manipulation technique due to its advantages of simple fabrication, prompt response, low power consumption and ease of integration with lab-on-a-chip systems [6]. Combination of electrowetting and surface roughness can be used to manipulate the droplet's wetting states. Electrowetting enables a droplet's transition from the Cassie state, in which the droplet rests on the tips of the roughness , to the Wenzel state, in which the droplet is in intimate contact with the surface cavities. The superhydrophobic surface is generally constructed by etching an array of square- or cylinder-shaped micro/nanopillars on the substrate, on which a droplet can stay in the Cassie state [7]. This well-designed nanopillars or nanoholes can also function as a Bragg grating. Thus, the potentially large tunability of droplet sagging depths can be integrated with the pillar-grating effect to form a tunable waveguide Bragg grating for filtering signals.

We here propose, for the first time, a tunable waveguide Bragg grating filter via incorporating a high degree of surface roughness on an electrowetting platform with an embedded waveguide.

2. Theory, results and discussion

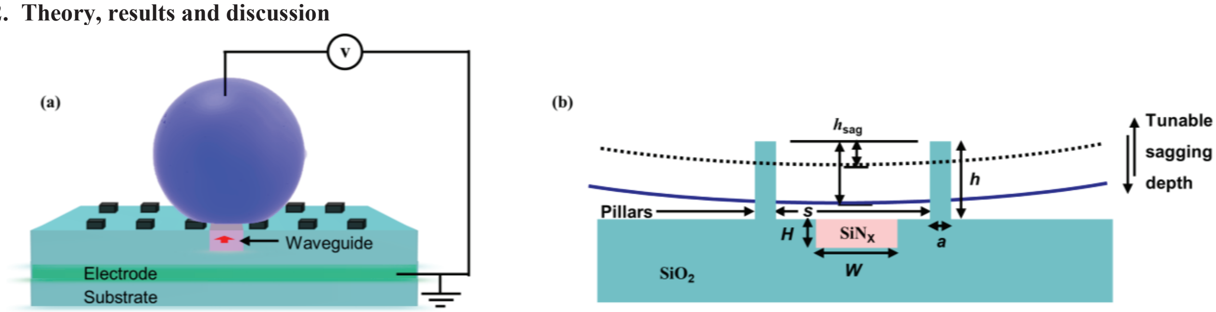

Fig. 1. (a) The 3D schematic of the proposed tunable droplet sagging filter on an EWOD platform; (b) The cross-section view. The blue lines indicate the tunable sagging depth of a droplet via EWOD.

Figure 1 shows a schematic of the proposed tunable Bragg grating filter composed of an array of square-shaped nanopillars on a planar waveguide. The proposed optical tunable filter is based on the tuning of the effective refractive index n_{eff} of the device through controlling the droplet's sagging depth by EWOD. Using EWOD, the Young-Lippmann contact angle θ_{YL} can be tuned and the droplet's morphology can be modulated accordingly, leading to a tunable sagging depth as shown in Table 1. To dynamically control the depth in grooves, the surface structures may need to satisfy a certain geometric criterion, in which the geometrical parameters of pillar have to be engineered to make the height of the pillars greater than the sagging depth of the droplet above. Based on this requirement, the periodic pillars designed for a reversible superhydrophobic surface with reversible sagging effect must follow

$$\frac{h}{a+s}=\frac{h}{\Lambda}>\left[\sqrt{2}-2\sqrt{f/\pi}\right]\frac{-1+\sin\theta_Y}{2\cos\theta_Y}$$

where h is the height of square pillars, a is the pillar width, s is the gap between pillars (see Figure 1(b)). For the square shaped pillars, $f=[a/(a+s)]^2 = (a/\Lambda)^2$ where $\Lambda=a+s$ is the period of the pillars. For example, if the surface is treated to be hydrophobic by spin coating of Teflon, θ_Y on the surface is 110°. Then each lower bound value of h / (a + s) will correspond to a given value of f as the black line shown in Figure 2. When the area fraction of solid-liquid contact f is 0.0625, the lower bound value of $h/(a+s)$ is ~ 0.1. Thus if the value of $a+s$ equals to 1555 nm, the lower bound value of h is ~ 155 nm as the black dot shown in Figure 2.

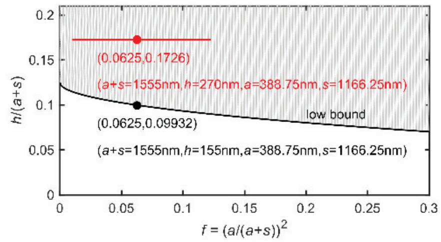

Figure 2. Estimated low bound value of the ratio $h/(a+s)$ for the surface with θ_Y of 110°.. Note that this range is above the low bound, which satisfy the requirement for reversible sagging effect.

Table. 1 Young-Lippmann angle vs. droplet's sagging depth

θ_{YL} (°)	92	93	94	95	96
h_{sag} (nm)	213.2	172.6	125.2	83.5	27.7

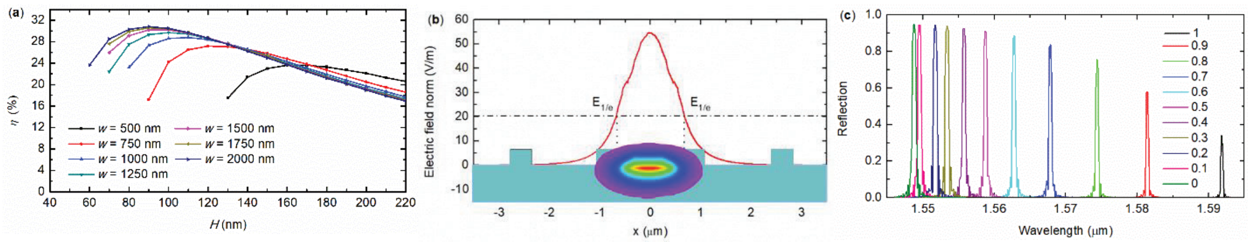

Fig. 2. (a) Mode confinement factor η with respect to waveguide geometry; (b) Mode field distribution with W = 1 μm, H = 110nm; (c) Wavelength tuning of the waveguide Bragg filter.

In order to implement the proposed optical filter, the pillars designed for a superhydrophobic surface above have to be further designed for compatibly meeting the optical rules of a waveguide Bragg grating at the same time. SiN_x material is utilized as the waveguide and has a refractive index of 2.48 at 1550 nm. The substrate is SiO_2 with a refractive index of 1.45. Mode confinement factor in cladding and mode field distribution are plotted in Figure 2(a) and (b). Here, the strip waveguide width of W and height H are fixed at 1 μm and 110 nm, which can give a high mode confinement factor in cladding for effective tuning and can yet still maintain single TE mode. Due to an exponential decay of the electric field in cladding, and x = 650 nm which is the position that the electric field to decay away to 1/e its maximal value, pillars should be distributed symmetrically on the side of the strip waveguide and around the 1/e position rather than right above the waveguide avoiding strong interactions resulting in broader bandwidth. Thus, the grating period ∧, pillar width w and pillar gap s are fixed at 1555 nm, 388.75 nm and 1166.25 nm. The effective refractive index of the fundamental TE mode n_{eff} is calculated to be 1.494, so that the center Bragg wavelength is approximately 1549 nm according to the Bragg equation $\lambda_B = 2\Lambda n_{eff}/m$. In addition, the pillar height h is 270 nm, corresponding to the electric field to decay away to 1/e its maximal value in y direction. Noted that, the ratio of pillar height h to pillar period ∧ is ~ 0.1726 (0.1726 is the ordinate value of the red line in Figure 2), which can meet the pillar design for a reversible superhydrophobic surface.

For this filter, the variation of sagging, in term of the ratio of h_{sag}/h, from 0 to 1 (corresponding to sagging depth h_{sag} varying from 0 nm to 270 nm) provides a continuous shift of the center wavelength of the Bragg filter over 43 nm from 1548.75 nm to 1591.83 nm.

3. Conclusion

The tuning of a chip waveguide Bragg grating via electrowetting is demonstrated. Applying electrowetting to the droplet results in a tunable sagging depth and thus provides a 43 nm shift in the reflection spectrum. This work was supported by National Natural Science Foundation of China (61775008).

4. References

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