Ultra-Compact Plasmonic Microresonator with Efficient Thermo-Optic Tuning, High Quality Factor and Small Mode Volume

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Abstract: We propose an ultra-compact plasmonic microresonator with high thermo-optic tuning efficiency (~ 4 nm/100 K), high quality factor (~ 350), and small mode volume (~ 0.01 μm^3). This microresonator has potential in on-chip components, thermal sensing, and micro/nano-lasing.
OCIS codes: (240.6680) Surface plasmons; (230.5750) Resonators

1. Introduction

Resonators at micro/nano scale found a lot of applications ranging from light sources, passive on-chip photonic elements, bio-sensing and so on [1]. Specifically, when the resonance can be tuned (e.g. electric-optic, thermo-optic, Kerr effect, etc.), resonators can be more flexible and functional. Meanwhile, for a resonator, it is advantageous to reduce its footprint and this is beneficial for its integration with other components. Plasmonics are promising candidates in the miniaturization and functionality improvement of resonators, since the mode energy can be tightly confined at the interface of metal and dielectric capable of breaking the limitation of diffraction [2]. Moreover, this tightly confined mode can increase the light-matter interaction, which offers a lot of opportunities for more efficient resonance tuning and control.

In this paper, we propose a new type of plasmonic resonator consisting of a ZnO dielectric ring placed on a silver chip, which has ultra-compact size and whispering-gallery (WG) like travelling modes are supported at the ZnO-silver interface. This resonator can simultaneously maintain ultra-small mode volume (~ 0.01 μm^3) and relatively high quality factor (~ 350). Moreover, the simulation results show that due to the large thermo-optic coefficient (TOC) of ZnO and silver, the resonance of the WG-like modes can be efficiently tuned by temperature control. Additionally, the temperature control can be fulfilled by various mechanisms (e.g. the electric current induced heating). This type of plasmonic resonator might see potential applications in wavelength-selective on-chip elements, thermal sensing, etc.

2. Resonator structure and results

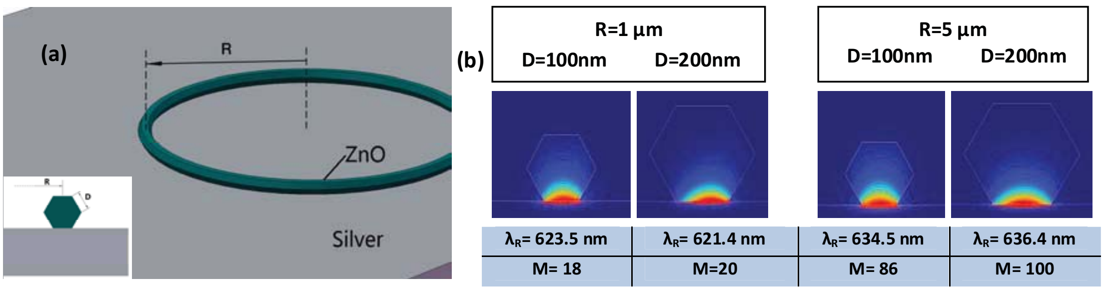

Fig. 1 (a) 3D structure illustration of the proposed plasmonic microresonator. (b) Energy density distribution and contour plot under certain geometrical parameters.

The proposed resonator consists of a ZnO ring on a silver substrate, as illustrated in Fig. 1(a). The inset shows the cross-section of the resonator, where a hexagonal shape of the ZnO can be seen. At the interface of the ZnO and silver substrate, surface plasmon polariton (SPP) can be supported. Due to the circular geometrical structure, this SPP can form a WG-like wave. This kind of WG-like mode can be characterized by am azimuthal mode number M, which determines the number of mode field maxima in a round trip. In Fig. 1(b), we plot the energy density distribution at the cross-section view each with a resonance in the 630 nm band under four sets of geometrical parameters. The simulation is based on a full-vector finite-element method [3]. The silver is modeled by a Drude model (fitting the Johnson and Christy's experimental data [4]) and ZnO's permittivity is obtained from a Sellmeier equation [5]. This mode is similar to the plasmon mode supported by a dielectric loaded surface plasmon polariton (DLSPP) waveguide in spite of the ring-resonator structure [6]. Different from the straight waveguide, the WG-like mode will slightly extend outwards due to the bending radiation, which can also be seen from the contour of the mode energy density shown in Fig. 1(b).

For a resonator, quality factor (Q) and mode volume (V) are two key parameters. Due to the high absorption loss from metal, plasmonic resonators usually have a relatively low quality factor compared with their dielectric counterparts. In our proposed structure, the area of dielectric-metal contact interface depends on the side length of hexagonal shape of ZnO, which could be reduced to ~ 100 nm or smaller while still maintaining a highly confined mode [6]. The mode volume of the proposed structure can be calculated by $V = \iiint W(\vec{r}) d^3(\vec{r}) / W(\vec{r})_{\max}$, where $W(\vec{r}) = \frac{1}{2}[\mathrm{Re}[\frac{d\{\varepsilon(\vec{r})\omega\}}{d\omega}]|\vec{E}(\vec{r})|^2 + \mu|\vec{H}(\vec{r})|^2]$ is the energy density.

Fig. 2(a) shows the dependence of Q and V on the side length D of the hexagonal shape under two different ring radius of 1 and 5 μm, respectively. It can be seen that, with a variation of D from 80 to 200 nm, a relatively high quality factor around 350 can be always obtained. Meanwhile, the mode volume slightly increases from 0.1 to 0.22 μm^3 with R=5 μm and 0.02 to 0.038 μm^3 with R=1 μm. It can be clearly seen that, the mode volume is smaller for a smaller ring radius R without significant sacrifice on the total quality factor. With the increase of hexagonal side length, it shows negligible impact on the quality factor but a tendency to increase the mode volume of the resonator. This indicates that, using hexagonal ZnO as the dielectric material provides possible way to further reduce the resonator size while maintaining favorable performance.

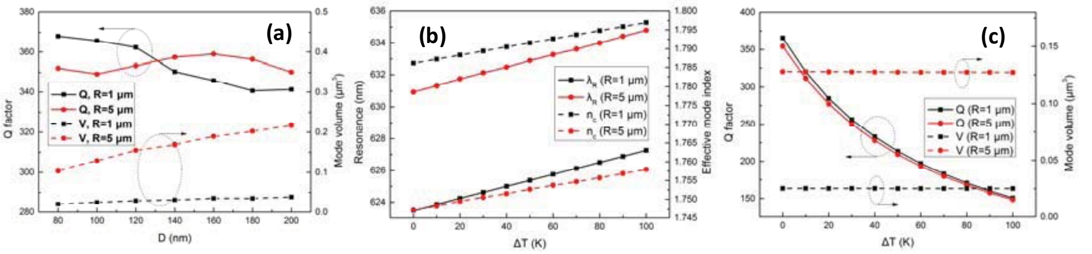

Fig. 2 (a) Quality factor and mode volume versus side length D of the hexagonal shape of ZnO. (b) Resonance wavelength and effective mode index vs. temperature change. (c) Quality factor and mode volume vs. temperature change.

In order to achieve resonance tuning, we investigate the thermo-optic effect on the resonance. In simulations, the TOC of silver and ZnO are taken from literatures [6, 7]. The results are shown in Fig. 2(b). It is clear that, with a radius of 5 μm, a 100 K temperature change from room temperature (293 K) can result in the resonance change from 630.9 to 634.8 nm, while the effective mode index n_{eff} (n_{eff}=mλ_R/2πR) changes from 1.747 to 1.758. Hence, the sensitivity of thermo-optic resonance tuning is assessed to be ~ 4 nm/100 K. Meanwhile, when the temperature is increased by 100 K, the quality factor drops from 354 to 148 as shown in Fig. 2(c). Such phenomenon can be explained with the fact that silver becomes more absorbable at higher temperature, resulting in the decrease of the total quality factor. The results for R=1 μm show similar trend for both cases. Additionally, the mode volume keeps almost unchanged with the change of temperature, still in sub-μm^3 scale.

3. Acknowledgements

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4. References

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