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به دام اندازی نانو ذرات با استفاده از موجبرهای نواری با مقطع مثلثی و نواری با شیار V-شکل

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چکیده- در این مقاله، بصورت عددی نشان داده شده است که موجبرهای نواری با مقطع مثلثی و نواری با شیار V-شکل در مقایسه با موجبرهای نواری متداول با مقطع مستطیلی قابلیت بسیار بالاتری در به دام اندازی نانوذرات دارند. مطابق محاسبات انجام گرفته حداکثر نیروی به دام اندازی وارد بر یک ذره با شعاع ۵ نانومتر از سوی موجبر نواری با مقطع مثلثی و نواری با شیار V-شکل به ترتیب ۸/۳ و ۱۴ برابر حداکثر نیروی به دام اندازی توسط موجبر نواری با مقطع مستطیلی می‌باشد.

کلید واژه- انبرک نوری، به دام اندازی نوری، موجبر نوری

Nano-Particle Trapping by Wedge and V-Groove Waveguides

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Abstract- In this paper, we numerically show that Silicon-on-Insulator (SOI) based wedge and V-groove waveguides have much higher capability to trap nanoparticles compared with the traditional stripe waveguides. According to the calculations, the maximum trapping force exerted by the wedge and V-groove waveguides to a 5 nm radius nanoparticle can be 8.3 and 14 times greater than that of the stripe waveguide respectively.

Keywords: Optical tweezer, Optical Trapping, Optical Waveguide.

1. Introduction

Optical tweezers have found a number of applications in the biological sciences for non-invasive studies of bio-cells. But, traditional free-space optical tweezers are massive and expensive apparatus which require professional operators. Also, near-field optical trapping systems based on the evanescent field of the photonic structures enable low-cost on-chip optical trapping at dimensions beyond diffraction limit [1-4].

A waveguide-based particle trapping system as a near-field optical tweezer has great advantages for particle trapping and transporting in optofluidic chips due to its simple fabrication and integration process using lithographic methods [5]. However, further reduction in the particle size in nanoscale (especially below 100 nm) leads to a weak optical trapping [6, 7]. The smaller the particle size the weaker the gradient and viscous drag forces, and hence the more difficult to be trapped. In other words, trapping the smaller particles require higher beam intensities [8]. Hence the input power of the device should be increased for effective trapping of these nanoparticles. But it is not a proper solution especially for on-chip and portable systems. Furthermore, high power optical fields may damage biological trapped samples. Some techniques have been proposed in the recent years to overcome these challenges and increase the exerted optical forces on the nanoparticles, but they suffer from fabrication complexity and propagation loss [9, 10].

In this paper, we propose a new application for SOI-based wedge and V-groove waveguides in the optical trapping area and compare them with the traditional stripe waveguide. According to the results presented in the next sections, these waveguides have impressive capability in trapping of the nanoparticles. Fabrication of these waveguides relies on optical lithography followed by precise anisotropic potassium hydroxide (KOH) etching. The KOH etching on a <100> silicon wafer can carve a triangular groove with an angle of 54.7° with respect to the surface and create the wedge and V-groove waveguides [11, 12].

2. Theoretical Models and Methods

The optical force exerted on a particle can be obtained by [13]:

$$\boldsymbol{F}_{op} = \oint_A \langle \boldsymbol{T}_M \rangle \cdot \boldsymbol{n} dA \qquad (1)$$

where $\langle \boldsymbol{T}_M \rangle$, $\boldsymbol{n}$ and dA are the time-averaged Maxwell Stress Tensor (MST), the unit vector normal to the outer surface of the particle volume over which the integral is taken, A, and differential surface element.

We can define the stability number, S, for a trapped particle by relating the work needed to release the particle compared to the random thermal motion of the particle [13]:

$$S = |U_{trap}| / k_B T \qquad (2)$$

where U_{trap} is the work needed to release the trapped particle, k_B is the Boltzmann constant and T is the temperature in Kelvin. Obviously, a larger S number leads to a more stable trap. The electromagnetic fields, optical forces and other related quantities is calculated by 3D finite element method (FEM) using COMSOL package. The free space wavelength of the input optical field is 1550 nm.

3. Design and Simulation Results

Fig. 1 shows the structures of the stripe, wedge, and V-groove waveguides and their normalized electric field distributions in the desired fundamental modes. The electric field distribution and its gradient in the cladding regions of the stripe and wedge waveguides are greater in the TM mode. These quantities in the cladding region of V-groove waveguide are larger in its TE mode. Therefore, to obtain larger trapping forces, the fundamental quasi-TM mode should be excited in the stripe and wedge waveguides, while the fundamental quasi-TE mode should be used in the V-groove waveguide.

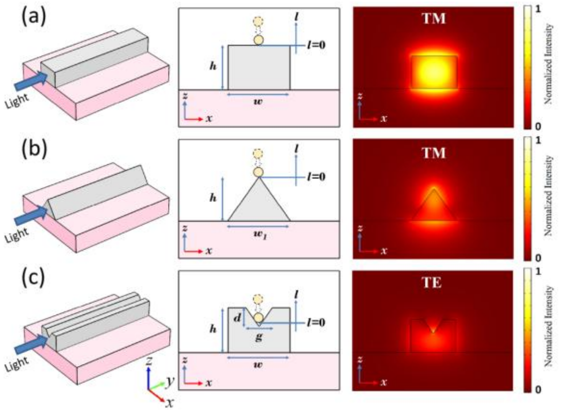

Fig. 1. Structure of the waveguides and normalized electric field distributions of the desired fundamental modes in the (a) Stripe, (b) Wedge and (c) V-groove waveguides. Geometrical parameters are set as follows: h = 360 nm, w = 500 nm, w_1 = 510 nm, d = 150 nm and g = 212 nm.

The geometrical parameters are chosen such that the TE and TM modes are separated from each other and the waveguides have a single quasi-TE and a single quasi-TM propagating mode [14, 15]. Even so, these parameters should be optimized for a specified application. The waveguides cores are formed by patterning the Si layer on a SOI substrate. The entire chip is immersed in water that serves as the top cladding in which the particles can move. Height of the cores is 360 nm and its width in the stripe and V-groove waveguides are 500 nm. Also, width of the wedge waveguide is 510 nm. Depth and width of the V-shape section are 150 nm and 212 nm, respectively. A polystyrene nanoparticle is used for studying the optical forces while material dispersion and absorption of Si, SiO_2, water and polystyrene are also considered [16].

Fig. 2 demonstrates the maximum trapping force in the z direction exerted to the particle versus the particle radius. As shown in the figure, this trapping force exerted on the particle over the stripe, wedge and V-groove waveguides is 0.066 pN/W, 0.55 pN/W and 0.98 pN/W for a 5 nm particle and 3.12 pN/W, 12.54 pN/W and 13.98 pN/W for a 20 nm particle respectively. It means that $F_{z,max}$ in the wedge waveguide is 8.3 times for the 5 nm particle and 4 times for the 20 nm particle stronger than that of the stripe waveguide.

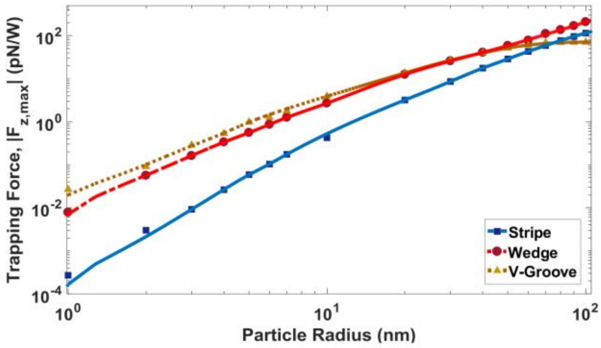

Fig. 2. Maximum Trapping force in the z direction versus particle radius with l = 3 nm.

In the V-groove waveguide $F_{z,max}$ is 14 times for the 5 nm particle and 4.4 times for the 20 nm particle stronger than that of the stripe one.

Fig. 3 illustrates the trapping force in the x direction, F_x, exerted to the 20 nm radius particle versus particle x-position and the profile of its potential well. In the V-groove waveguide, particles are physically confined inside V-shape for x direction. These robust increases in the trapping forces result deeper potential wells and larger stability numbers for the trapped particles.

According to the calculations, stability number of the 5 nm polystyrene particle is 0.70 W^{-1}, 2.21 W^{-1} and 3.84 W^{-1} for the stripe, wedge and V-groove waveguides respectively, indicating 3.1 and 5.4 times larger in the wedge and V-groove with respect to the stripe waveguide. In the same manner, stability number of the 20 nm polystyrene particle is 32.9 W^{-1}, 79.6 W^{-1} and 99.6 W^{-1} for the stripe, wedge and V-groove waveguides respectively.

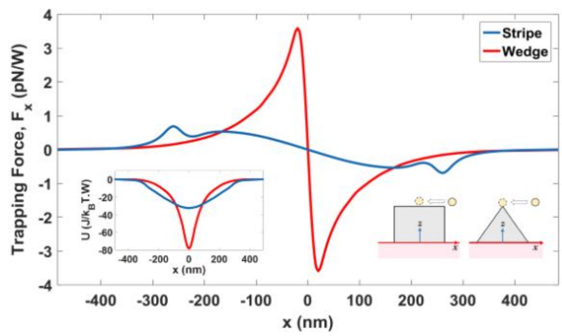

Fig. 3. Trapping force in the x direction exerted on the 20 nm radius particle versus particle x-position and l = 3 nm. The inset shows the potential well for the particle in the x direction.

These quantities show 2.4 and 3 times larger stability number in the wedge and V-groove compared to the stripe waveguide for the 20 nm particle. Larger stability number leads to a more stable trap for the same input power or, in other words, a smaller required input power for the same depth of the potential well.

It should be mentioned that in the experimental works the surfaces is coated with a few nanometer surfactant layers to prevent the sticking of nanoparticles on the surface [17]. So, we assume a 3 nm layer on top of the waveguides in all calculations and simulations, therefore the minimum distance between the particles and the waveguides is 3 nm (l_{min} = 3 nm).

4. Conclusion

In conclusion, wedge and V-groove waveguides were proposed as appropriate devices for nanoparticle trapping. Their efficiency was studied numerically and compared with the stripe waveguide. According to the calculations, the trapping forces exerted by the wedge and V-groove waveguides to a 5 nm radius nanoparticle could be 8.3 and 14 times greater than that of the stripe one. Consequently, in terms of the trapping capability and ease of fabrication, the wedge and V-groove structures has significant advantages for nanoparticle manipulation in optofluidic chips.

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