ORIGINAL RESEARCH

Molecular buffer using a PANDA ring resonator for drug delivery use

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Abstract: A novel design of molecular buffer for molecule storage and delivery using a PANDA ring resonator is proposed. The optical vortices can be generated and controlled to form the trapping tools in the same way as the optical tweezers. In theory, the trapping force is formed by the combination between the gradient field and scattering photons, which is reviewed. By using the intense optical vortices generated within the PANDA ring resonator, the required molecules can be trapped and moved (transported) dynamically within the wavelength router or network, ie, a molecular buffer. This can be performed within the wavelength router before reaching the required destination. The advantage of the proposed system is that a transmitter and receiver can be formed within the same system, which is available for molecule storage and transportation.

Keywords: molecular buffer, molecular memory, molecular transceiver, molecular repeater, PANDA ring resonator

Introduction

Optical buffers are recognized as essential components in wavelength routers, in which the packets of data can be stored for resolving packet contention problems and also delay the outgoing packets.[1,2] In practice, the optical router patents have been proposed and recorded,[3–5] which can be useful for various applications. Recently, the promising techniques of microscopic volume trapping and transportation within the add/drop multiplexer have been reported in both theory[6] and experiment,[7] respectively, in which the transporter is known as an optical tweezer. Here, the optical tweezer generation technique has become a powerful tool for the manipulation of micrometer-sized particles. To date, the usefulness of static tweezers is well recognized. Moreover, the use of dynamic tweezers is now also understood in practical works.[8–10] Schulz et al[11] have shown that the transfer of trapped atoms between two optical potentials can be performed. In principle, optical tweezers use forces exerted by intensity gradients in the strongly focused beams of light to trap and move the microscopic volumes of matters, in which the other combination of force is induced by the interaction between photons, which is caused by photon scattering effects. In application, the field intensity can be adjusted and tuned, in which the desired gradient field and scattering force can form the suitable trapping force. Hence, the appropriate force can be configured for the transmitter/receiver, which can perform the long distance microscopic transportation.

In this paper, dynamic optical tweezers/vortices are generated using a dark soliton, bright soliton, and Gaussian pulse propagating within an add/drop optical multiplexer incorporating two nanoring resonators (PANDA ring resonator). The dynamic

behaviors of solitons and Gaussian pulses are well described by Tasakorn et al.[12] By using the proposed system, the transceiver can be integrated and performed by using a single device. Here, the use of the transceiver to form the transportation of microscopic volumes of matter, especially[13] for molecule transportation in liquid core waveguide,[14,15] drug delivery, and DNA transportation, in which the buffer is needed before reaching the required destination.

Theory

In operation, the trapping forces are exerted by the intensity gradients in the strongly focused beams of light to trap and move the microscopic volumes of matters, in which the optical forces are customarily defined by the relationship:[16]

$$F = \frac{Q n_m P}{c} \quad (1)$$

Here Q is a dimensionless efficiency, n_m is the refractive index of the suspending medium, c is the speed of light, and P is the incident laser power, measured at the specimen. Q represents the fraction of power utilized to exert force. For plane wave incidences on a perfectly absorbing particle, Q is equal to 1. To achieve stable trapping, the radiation pressure must create a stable, three-dimensional equilibrium. Because biological specimens are usually contained in aqueous media, the dependence of F on n_m can rarely be exploited to achieve higher trapping forces. Increasing the laser power is possible, but only over a limited range due to the possibility of optical damage. Q itself is therefore the main determinant of trapping force. It depends upon the numerical aperture (NA), laser wavelength, light polarization state, laser mode structure, relative index of refraction, and the geometry of the particle.

Furthermore, in the Rayleigh regime, trapping forces decompose naturally into two components. Since, in this limit, the electromagnetic field is uniform across the dielectric, particles can be treated as induced point dipoles. The scattering force is given by:[16]

$$F_{scatt} = n_m \frac{\langle S \rangle \sigma}{c}, \quad (2)$$

$$\sigma = \frac{8}{3} \pi (kr)^4 r^2 \left(\frac{m^2 - 1}{m^2 + 2} \right)^2 \quad (3)$$

Here σ is the scattering cross section of a Rayleigh sphere with radius r. $\langle S \rangle$ is the time averaged Poynting vector, n is the index of refraction of the particle, $m = n/n_m$ is the relative index, and $k = 2\pi n_m / \lambda$ is the wave number of the light. The scattering force is proportional to the energy flux and points

along the direction of the propagation of the incident light. The gradient field (F_{grad}) is the Lorentz force acting on the dipole induced by the light field. It is given by:[16]

$$F_{grad} = \frac{\alpha}{2} \nabla \langle E^2 \rangle, \quad (4)$$

where

$$\alpha = n_m^2 r^3 \left(\frac{m^2 - 1}{m^2 + 2} \right) \quad (5)$$

is the polarizability of the particle. The gradient force is proportional and parallel to the gradient in energy density (for $m > 1$). The large gradient force is formed by the large depth of the laser beam. The stable trapping requires that the gradient force is in the $-\hat{z}$ direction, which is against the direction of incident light (dark soliton valley). It is greater than the scattering force. By increasing the NA, when the focal spot size is decreased, the gradient strength is increased,[16,17] which happens within a tiny system, for instance, a nanoscale device such as the nanoring resonator.

In our proposal, the trapping force is formed by using a dark soliton, in which the valley of the dark soliton is generated and controlled within the PANDA ring resonator by the control port signals. In this paper, we used the same theory of optical trapping and ring resonator, in which the simulation results and applications are differed from the previous work.[18]

From Figure 1, the output field (E_{t1}) at the through port is given by:[19]

$$E_{t1} = A E_{i1} - B E_{i2} e^{-\frac{\alpha L}{2} - j k_n \frac{L}{2}}$$
$$- \left[\frac{C E_{t1} \left(e^{-\frac{\alpha L}{2} - j k_n \frac{L}{2}} \right)^2 + D E_{i2} \left(e^{-\frac{\alpha L}{2} - j k_n \frac{L}{2}} \right)^3}{1 - F \left(e^{-\frac{\alpha L}{2} - j k_n \frac{L}{2}} \right)^2} \right] \quad (6)$$
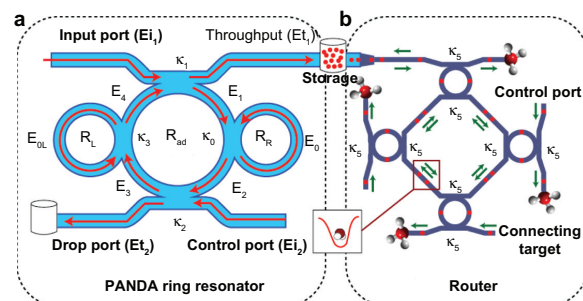

Figure 1 Schematic diagram of a buffer system, where (**a**) a PANDA ring resonator, (**b**) a wavelength router where R_{add} is the add/drop filter radius and R_R and R_L are the right and left ring resonator radii, respectively.

where

$$A = \sqrt{(1-\gamma_1)(1-\gamma_2)},$$
$$B = \sqrt{(1-\gamma_1)(1-\gamma_2)\kappa_1(1-\kappa_2)}E_{0L},$$
$$C = \kappa_1(1-\gamma_1)\sqrt{(1-\gamma_2)\kappa_2}E_0E_{0L},$$
$$D = (1-\gamma_1)(1-\gamma_2)\sqrt{\kappa_1(1-\kappa_1)\kappa_2(1-\kappa_2)}E_0E_{0L}^2, \quad \text{and}$$
$$F = \sqrt{(1-\gamma_1)(1-\gamma_2)(1-\kappa_1)(1-\kappa_2)}E_0E_{0L}.$$

Here, E_t and E_d represent the optical fields of the through port and drop ports, respectively. $\beta = kn_{eff}$ is the propagation constant, n_{eff} is the effective refractive index of the waveguide, and the circumference of the ring is $L = 2\pi R$, where R is the radius of the ring. κ_1 and κ_2 are the coupling coefficients of the add/drop filters, $k_n = 2\pi/\lambda$ is the wave propagation number for in a vacuum, and the waveguide (ring resonator) loss is $\alpha = 0.5$ dBmm^{-1}. The fractional coupler intensity loss is $\gamma = 0.1$. In the case of the add/drop device, the nonlinear refractive index does not affect the system, therefore, it is neglected. The electric fields E_0 and E_{0L} are the field circulated within the nanoring at the right and left side of add/drop optical filter.

The power output (P_{t1}) at through port is written as:

$$P_{t1} = |E_{t1}|^2. \tag{7}$$

The output field (E_{t2}) at drop port is expressed as:[19]

$$E_{t2} = \sqrt{(1-\gamma_2)(1-\kappa_2)}E_{i2}$$
$$- \left[\frac{\sqrt{(1-\gamma_1)(1-\gamma_2)\kappa_1\kappa_2}E_0E_{i1}e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}} + XE_0E_{0L}E_{i2}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2}{1-YE_0E_{0L}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2} \right], \tag{8}$$

where

$$X = (1-\gamma_2)\sqrt{(1-\gamma_1)(1-\kappa_1)\kappa_2(1-\kappa_2)},$$
$$Y = \sqrt{(1-\gamma_1)(1-\gamma_2)(1-\kappa_1)(1-\kappa_2)}$$

The power output (P_{t2}) at drop port is:

$$P_{t2} = |E_{t2}|^2. \tag{9}$$

In operation, the optical tweezers can be trapped, transported, and stored within the PANDA ring resonator and wavelength router, which can be used to form the microscopic volume (molecule) transportation and drug delivery via the waveguide,[18] in which the manipulation of trapped microscopic volumes within the optical tweezers has been reported.

Molecular buffer

Molecular buffers are devices that can be used to store or delay atoms/molecules for a period of time (see Figure 2), where light intensity and velocity can also be controlled, which was described by Rosenberry et al[20] and Lignie and Woerdman,[21] available for medical application. Molecular buffers are a new device, which are operated in the same way as gas buffers.[22] The polarizability of the particle is calculated by using equation (5), in this case, we assume that the sphere particle is polystyrene (n = 1.5894) and the liquid medium is water (n = 1.33), and the optical power which is required to trap particles of a certain size/polarizibility is 9.1W, which is the slope as shown in Figure 3A.

In simulation, the bright soliton with center wavelength at 1.50 μm, peak power 2W, pulse 35fs is input into the system via the input port, and the coupling coefficients are given as $\kappa_0 = 0.5$, $\kappa_1 = 0.35$, $\kappa_2 = 0.1$, and $\kappa_3 = 0.35$, respectively. The ring radii are $R_{add} = 10$ and 30 μm, $R_R = 50$ and 100 nm, and $R_L = 50$ and 100 nm, respectively. To date, the evidence of a practical device with a radius of 30 nm has been reported by Piyatamrong et al.[19] A_{eff} are 0.50, 0.25, and 0.25 μm^2. In this case, the dynamic tweezers (gradient fields) can be in the form of bright solitons, Gaussian pulses, and dark solitons, which can be used to trap the required microscopic volume. There are four different center wavelengths of tweezers generated; the dynamical movements are seen in Figure 4, where (a) $|E_1|^2$, (b) $|E_2|^2$, (c) $|E_3|^2$, (d) $|E_4|^2$, (e) through port, and (f) drop port signals, where in this case all microscopic volumes are received by the drop port. In practice, the fabrication parameters which can be easily controlled are the ring resonator radii instead of the coupling constants.

The important aspect of the result is that the tunable tweezers can be obtained by tuning (controlling) the add (control) port input signal, in which the required amount of microscopic volume (atom/photon/molecule) can be obtained
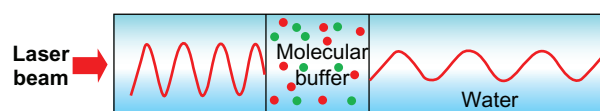

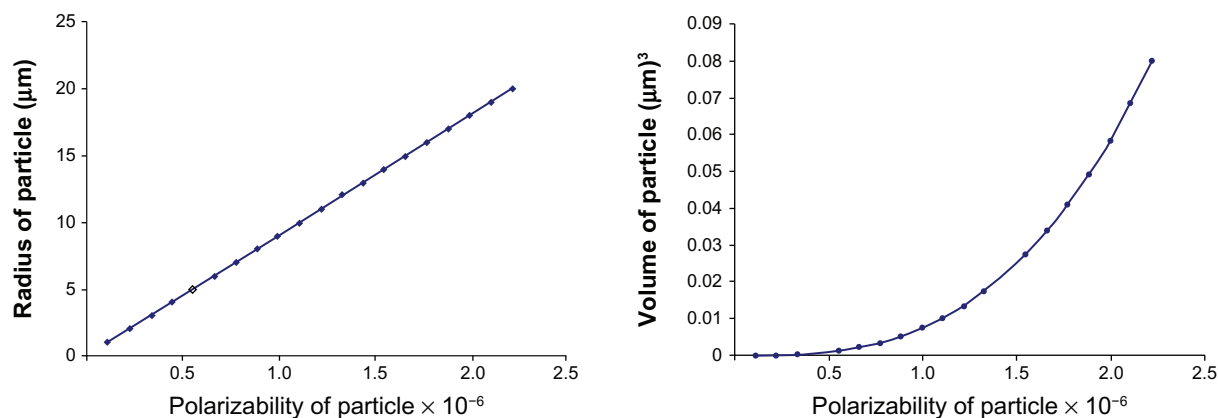**Figure 2** Schematic of molecular buffer work in core wave guide.

Figure 3 Graph of optical power which is required to trap the particle of a certain size/polarizability.

and seen at the drop/through ports, otherwise they propagate within a PANDA ring before collapsing/decaying into the waveguide. More results of the optical tweezers generated within the PANDA ring are shown in Figure 5, where in this case, the bright soliton is used as the control port signal to obtain the tunable results. The output optical tweezers of the through and drop ports with different coupling constants are

as shown in Figure 5A, while the different wavelength results are as shown in Figure 5B, which can be performed by the selected targets. In application, the trapped microscopic volumes (molecules) can move into the wavelength router via the through port, while the retrieved microscopic volumes are received via the drop port (connecting target). The advantage of the proposed system is that the transmitter and
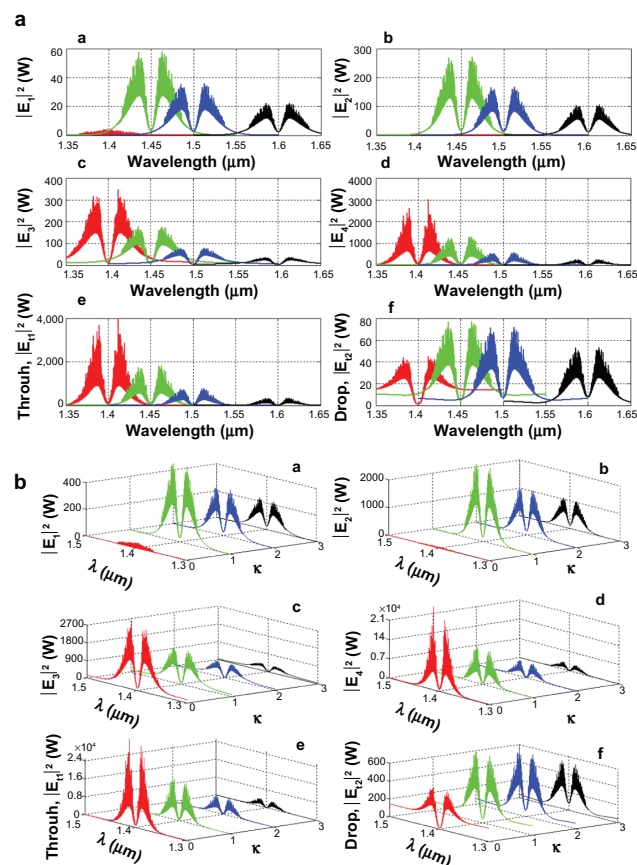

Figure 4 Result of the dynamic tweezers within the buffer with different (**a**) wavelengths and (**b**) coupling constants, where R_{add} = 10 μm, $R_R = R_L$ = 100 nm.
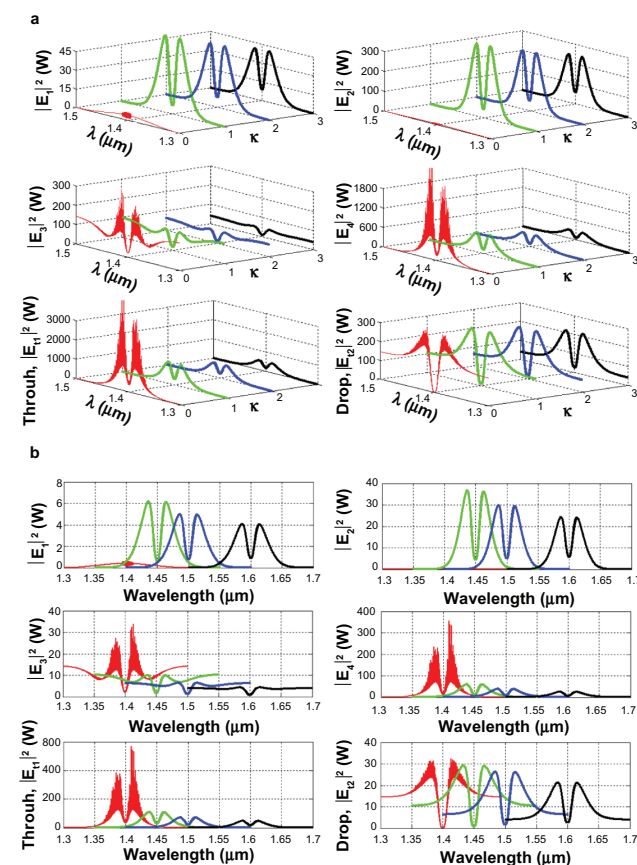

Figure 5 Result of the dynamic tweezers within the buffer with different (**a**) coupling constants and (**b**) wavelengths, where R_{add} = 30 μm, $R_R = R_L$ = 50 nm.

receiver can be fabricated on-chip and alternatively operated by a single device.

The magnitude of the optical trapping force is the pico Newton, which depends upon the relative refractive index of particle, which was given by Kumar et al.[23] The particle radius was given by Hu et al,[24] Fischer and Sørensen,[25] and Nieminen et al,[26] which is located in the cavity. It decreases with a reduction in refractive indices compared to the host medium.

Conclusion

We have proposed a new system that can be used to trap (delay) and transport molecules into an optical waveguide by using optical tweezers, which can be used for drug storage and as a delivery system. By utilizing the reasonable dark soliton input power, the dynamic tweezers can be controlled and stored (delayed) within the system before reaching the final destination. Tweezer amplification is also available by using the nanoring resonators, in which the signals can be modulated via the control port as shown in Figures 4B and 5A. In conclusion, we have shown that the use of a transceiver for long distance microscopic volume by using the proposed system, in which the drug delivery or molecular communication can be performed via the wavelength router to the required (connecting) targets. However, the problems of large microscopic volume and neutral matter may cause a problem, in which the pursuit of new guide pipes and media,[27] for instance, nano tubes and specific gases, will be the issue of investigation.

Acknowledgments

Disclosure

The authors report no conflicts of interest in this work.

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