Optical vortices generated by a PANDA ring resonator for drug trapping and delivery applications

Nathaporn Suwanpayak,[1] Muhammad Arif Jalil,[2] Chat Teeka,[1] Jalil Ali[3], and Preecha P. Yupapin[1,*]

[1]*Nanoscale Science and Engineering Research Alliance, Advanced Research Center for Photonics, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand*
[2]*Ibnu Sina Institute of Fundamental Science Studies (IIS), Nanotechnology Research Alliance, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia*
[3]*Institute of Advanced Photonics Science, Nanotechnology, Research Alliance, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia*
**kypreech@kmitl.ac.th*

Abstract: We propose a novel drug delivery system (DDS) by using a PANDA ring resonator to form, transmit and receive the microscopic volume by controlling some suitable ring parameters. The optical vortices (gradient optical field/well) can be generated and used to form the trapping tool in the same way as the optical tweezers. The microscopic volume (drug) can be trapped and moved (transported) dynamically within the wavelength router or network. In principle, the trapping force is formed by the combination between the gradient field and scattering photons, which has been reviewed. The advantage of the proposed system is that a transmitter and receiver can be formed within the same system, which is called transceiver, in which the use of such a system for microscopic volume (drug volume) trapping and transportation (delivery) can be realized.

OCIS codes: (140.7010) Laser trapping; (350.4855) Optical tweezers or optical manipulation; (080.4865) Optical vortices; (140.4780) Optical resonators; (190.4360) Nonlinear optics, devices.

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1. Introduction

Much effort has been made to explain the nature of optical forces and to describe them quantitatively by the establishment of theoretical models. This requires a detailed knowledge of the incident electromagnetic field that impinges on the object and of the properties of the object, which changes the incident field distribution by scattering, absorption or reemission of photons [1].The theory of optical vortices soliton developed to date assumes a background of constant amplitude and is able to capture a number of interesting features of dynamic vortices. Understanding this dynamics is important for future application of soliton vortices in steerable all optical switching devices based on the concept of dark /bright soliton [2]. Recently, he promising techniques of microscopic volume trapping and transportation within the add/drop multiplexer have been reported in both theory [3] and experiment [4], respectively. To date, the optical tweezer technique has become a powerful tool for manipulation of micrometer-sized particles in three spatial dimensions. Initially, the useful static tweezers are recognized, and the dynamic tweezers are now realized in practical works [5–7]. Schulz et al [8] have shown that the transfer of trapped atoms between two optical potentials could be performed. In principle, an optical tweezers use forces exerted by intensity gradients in the strongly focused beams of light to trap and move the microscopic volumes of matters. Moreover, the other combination of force is induced by the interaction between photons, which is caused by the photon scattering effects. In practice, the field intensity can be adjusted and tuned to form

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the suitable trapping potential, in which the desired gradient field and scattering force can be formed the suitable trapping force.

In biological applications of optical trapping and manipulation, it is possible to remotely apply controlled forces on living cells, internal parts of cells, and large biological molecules without inflicting detectable optical damage. This has resulted in many unique applications, where one of the most important of them is in the drug delivery and trapping study [9]. Several researchers have developed the drug delivery system, which can be designed to improve the pharmacological and therapeutic. There is attempt seeks the way cures that be able to achieve through specific surface receptors and fast, where the controlled drug delivery can help parenteral and route drug delivery. For the conventional methods of drug delivery management, usually, drug delivery at constant controlled rate is preferable. However, a better method may be in response to the physiological needs of the body. Moreover, the several advantages over conventional molecules are nanoparticle networks that have been proposed for controlling the release of high molecular weight biomolecules and drug molecules [10–15].

In this paper, we propose the use of drug delivery system using the optical vortices within a PANDA ring resonator in which the dynamic optical 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). We design the drug delivery system is a PANDA ring resonator as the pump atom/molecules into router network, which is InGaAsP/InP material [16–18]. For the router network, we design a liquid-core router channel as fluidic channel, in which are dynamically smooth and easily transportation of the atom/molecules [19]. The dynamic behaviors of solitons and Gaussian pulses are analyzed and described [2,20]. To increase the channel multiplexing, the dark solitons with slightly different wavelengths are controlled and amplified within the tiny system. The trapping force stability is simulated and seen when the Gaussian pulse is used to control via the add (control) port. In application, the optical vortices (dynamic tweezers) can be used to store (trap) photon, atom, molecule, DNA, ion, or particle, which can perform the dynamic tweezers. By using the hybrid transceiver, where the transmitter and receiver parts can be integrated by a single system. Here, the use of the transceiver to form the hybrid communication of those microscopic volumes of matters in the nanoscale regime can be realized, especially, for drug delivery application.

2. Optical vortex generation

In principle, the optical tweezers use force that are exerted by the intensity gradients in the strongly focused beam of light to trap and move the microscopic volume of matter, in which the optical force are customarily and may be described for a trapped mass/volume that give a viscous damping defined by the relationship equate optical force with Stokes force as follow [21,22].

$$F = \frac{Qn_m P}{c} = \gamma_0 \dot{x} \tag{1}$$

where

$$\gamma_0 = 6\pi r \rho v \tag{2}$$

where $\dot{x}$ is velocities of volume, 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. γ_0 is the stokes' drag term (viscous damping), r is a particle/volume radius, v is kinematic viscosity and ρ is fluids of density, Q is a dimensionless efficiency. Q represents the fraction of power utilized to exert force. For plane waves incident on a perfectly absorbing particle, Q = 1. To achieve

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stable trapping, the radiation pressure must create a stable, three-dimensional equilibrium. Because biological specimens are usually contained in aqueous medium, the dependence of F on nm 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 NA, laser wavelength, light polarization state, laser mode structure, relative index of refraction, and geometry of the particle.

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

$$F_{scatt} = \frac{\langle S \rangle \sigma}{c} \tag{3}$$

where

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

where is the scattering cross section of a Rayleigh sphere with radius *r*. *S* 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. Scattering force is proportional to the energy flux and points along the direction of propagation of the incident light. The gradient force is the Lorentz force acting on the dipole induced by the light field. It is given by

$$F_{grad} = \frac{\alpha}{2} \nabla \langle E^2 \rangle, \tag{5}$$

where

$$\alpha = n_m^2 r^3 \left(\frac{m^2 - 1}{m^2 + 2} \right) \tag{6}$$

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, in which the stable trapping requires that the gradient force in the $-\hat{z}$ direction, which is against the direction of incident light (dark soliton valley), and it is greater than the scattering force. By increasing the NA, when the focal spot size is decreased, the gradient strength is increased [23], which can be formed within the tiny system, for instance, nanoscale device (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. From Fig. 1, the output field (E_{t1}) at the through port is given by [24]. We are looking for the system that can generate the dynamic tweezers (optical vortices), in which the microscopic volume can be trapped and transmission via the communication link. Firstly, the stationary and strong pulse that can propagate within the dielectric material (waveguide) for period of time is required. Moreover, the gradient field is an important property required in this case. Therefore, a dark soliton is satisfied and recommended to perform those requirements. Secondly, we are looking for the device that optical tweezers can propagate and form the long distance link, in which the gradient field (force) can be transmitted and received by using the same device. Here, the add/drop multiplexer in the form of a PANDA ring resonator which is well known and is introduced for this proposal, as shown in Figs. 1 and 2.

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To form the multi function operations, for instance, control, tune, amplify, the additional pulses are bright soliton and Gaussian pulse introduced into the system. The input optical field (E_{in}) and the add port optical field (E_{add}) of the dark soliton, bright soliton and Gaussian pulses are given by [19], respectively.

$$E_{in}(t) = A\tanh\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{Z}{2L_D}\right) - i\omega_0 t\right] \tag{7}$$

$$E_{control}(t) = A\sec h\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{Z}{2L_D}\right) - i\omega_0 t\right] \tag{8}$$

$$E_{control}(t) = E_0\exp\left[\left(\frac{Z}{2L_D}\right) - i\omega_0 t\right] \tag{9}$$

where A and z are the optical field amplitude and propagation distance, respectively. T is a soliton pulse propagation time in a frame moving at the group velocity, $T = t–\beta_1 z$, where β_1 and β_2 are the coefficients of the linear and second-order terms of Taylor expansion of the propagation constant. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. T_0 in equation is a soliton pulse propagation time at initial input (or soliton pulse width), where t is the soliton phase shift time, and the frequency shift of the soliton is ω_0. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When a soliton of peak intensity ($|\beta_2/\Gamma T_0^2|$) is given, then T_0 is known. For the soliton pulse in the microring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length ($L_{NL} = 1/\Gamma\phi_{NL}$). Here $\Gamma = n_2 k_0$, is the length scale over which dispersive or nonlinear effects makes the beam become wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths. Hence $L_D = L_{NL}$. For a Gaussian pulse in Eq. (9), E_0 is the amplitude of optical field.

When light propagates within the nonlinear medium, the refractive index (n) of light within the medium is given by

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}}P \tag{10}$$

with n_0 and n_2 as the linear and nonlinear refractive indexes, respectively. I and P are the optical intensity and the power, respectively. The effective mode core area of the device is given by A_{eff}. For the add/drop optical filter design, the effective mode core areas range from 0.10 to 0.50 μm^2, in which the parameters were obtained by using the related practical material parameters (InGaAsP/InP) [25]. When a dark soliton pulse is input and propagated within a add/drop optical filter as shown in Fig. 1, the resonant output is formed. Thus, the normalized output of the light field is defined as the ratio between the output and input fields [$E_{out}(t)$ and $E_{in}(t)$] in each roundtrip. This is given as [26].

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\left[1 - \frac{(1-(1-\gamma)x^2)\kappa}{(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2 + 4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\varphi}{2})}\right] \tag{11}$$

The close form of Eq. (11) indicates that a ring resonator in this particular case is very similar to a Fabry–Perot cavity, which has an input and output mirror with a field reflectivity, $(1–\kappa)$, and a fully reflecting mirror. κ is the coupling coefficient, and $x = exp(–\alpha L/2)$ represents a roundtrip loss coefficient, $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_{in}|^2$ are the linear and

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nonlinear phase shifts, $k = 2\pi/\lambda$ is the wave propagation number in a vacuum. L and α are the waveguide length and linear absorption coefficient, respectively. In this work, the iterative method is introduced to obtain the resonant results and similarly, when the output field is connected and input into the other ring resonators.

In order to retrieve the required signals, we propose to use the add/drop device with the appropriate parameters. This is given in the following details. The optical circuits of ring resonator add/drop filters for the through port and drop port can be given by Eqs. (12) and (13), respectively [27].

$$\left|\frac{E_t}{E_{in}}\right|^2 = \frac{\left[\begin{array}{l}\left(1-\kappa_1\right)+\left(1-\kappa_2\right)e^{-\alpha L} \\ -2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos\left(k_n L\right)\end{array}\right]}{\left[\begin{array}{l}1+\left(1-\kappa_1\right)\left(1-\kappa_2\right)e^{-\alpha L} \\ -2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos\left(k_n L\right)\end{array}\right]} \quad (12)$$

$$\left|\frac{E_d}{E_{in}}\right|^2 = \frac{\kappa_1\kappa_2 e^{-\frac{\alpha}{2}L}}{1+\left(1-\kappa_1\right)\left(1-\kappa_2\right)e^{-\alpha L}-2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos\left(k_n L\right)} \quad (13)$$

Here E_t and E_d represent the optical fields of the through port and drop ports, respectively. $\beta = kn_{\text{eff}}$ is the propagation constant, n_{eff} is the effective refractive index of the waveguide, and the circumference of the ring is $L = 2\pi R$, with R as the radius of the ring. The filtering signal can be managed by using the specific parameters of the add/drop device, and the required signals can be retrieved via the drop port output. 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 is not effect to the system, therefore, it is neglected.

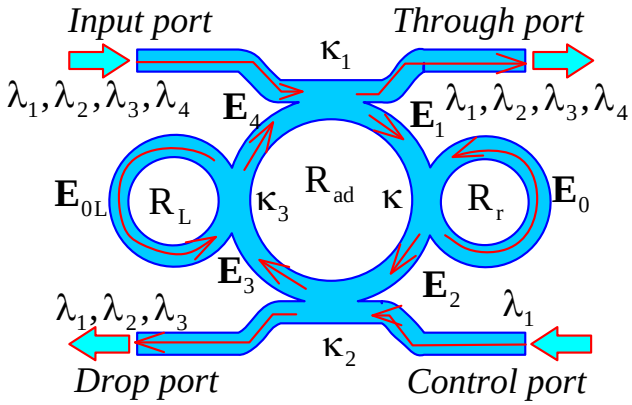

Fig. 1. Schematic diagram of a proposed PANDA ring resonator.

From Eq. (12), the output field (E_{t1}) at the through port is given by

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$$E_{t1} = AE_{i1} - BE_{i2}e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}} - \left[\frac{CE_{i1}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2 + DE_{i2}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^3}{1-E\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2}\right], \quad (14)$$

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

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

$$P_{t1} = \left|E_{t1}\right|^2. \quad (15)$$

The output field (E_{t2}) at drop port is expressed as

$$E_{t2} = \sqrt{(1-\gamma_2)(1-\kappa_2)}E_{i2} - \left[\frac{\sqrt{(1-\gamma_1)(1-\gamma_2)\kappa_1\kappa_2}E_0E_{i1}e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}} + XE_0E_{0L}E_{i2}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2}{1-YE_0E_{0L}\left(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}}\right)^2}\right], \quad (16)$$

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

$$P_{t2} = \left|E_{t2}\right|^2. \quad (17)$$

3. Drug trapping and delivery

By using the proposed design, the optical tweezers can be generated, trapped, transported and stored within the PANDA ring resonator and wavelength router as shown in Figs. 1 and 2, which can be used to form the microscopic volume transportation, i.e. drug delivery, via the waveguide [3,4]. Simulation results of the dynamic optical vortices within the PANDA ring are as shown in Fig. 3. In this case the bright soliton is input into the control port, and the trapped atoms/molecules are as shown in Fig. 3 (a)-3(f). The ring radii are R_{add} = 10μm, R_R = 4 μm and R_L = 4 μm, in which the evidence of the practical device was reported by the authors in reference [28]. A_{eff} are 0.50, 0.25 and 0.25 μm^2: In this case, the dynamic tweezers (gradient fields) can be in the forms of bright soliton, Gaussian pulses and dark soliton, which can be used to trap the required microscopic volume. There are five different center wavelengths of tweezers generated, where the dynamical movements are (a) $|E_1|^2$, (b) $|E_2|^2$, (c) $|E_3|^2$, (d) $|E_4|^2$, (e) through port and (f) drop port signals.

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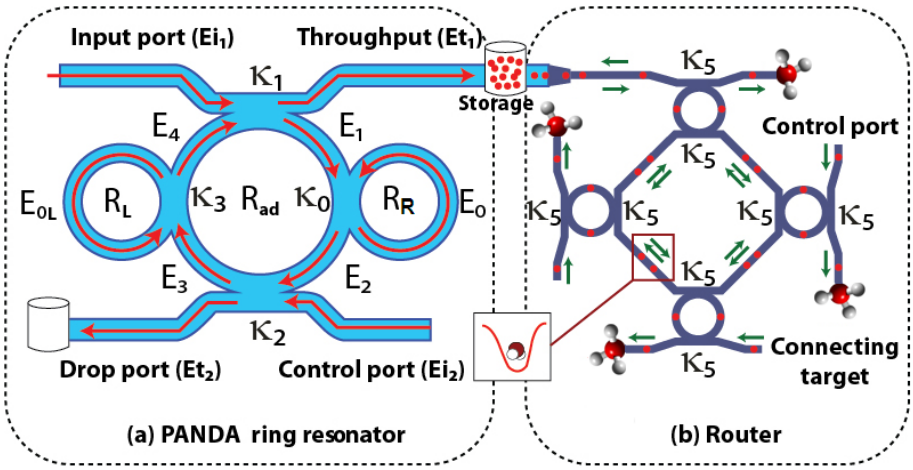

Fig. 2. A system of drug delivery and distribution using optical vortices.

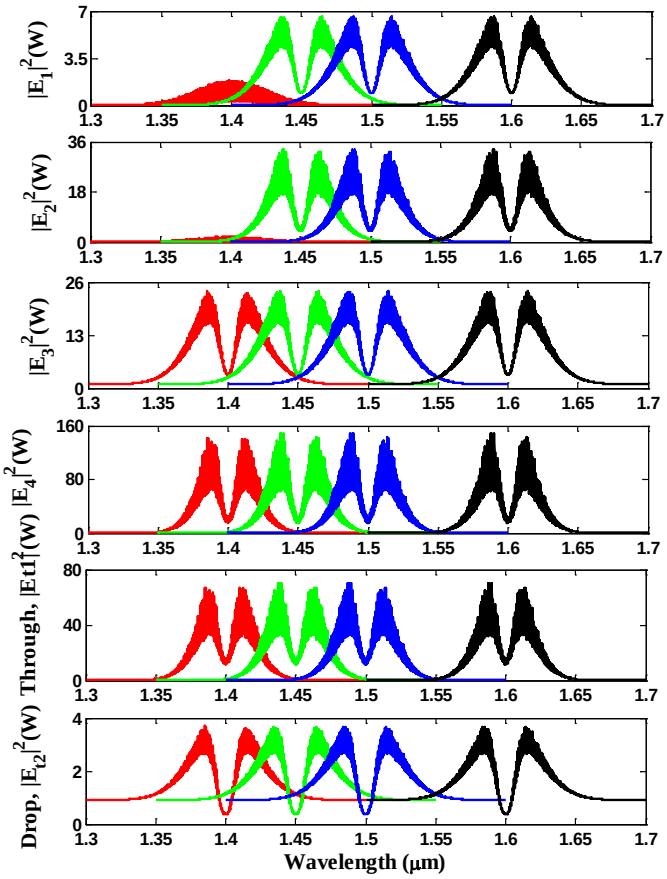

Fig. 3. Simulation result of four potential wells (optical vortices/tweezers) with four different center wavelengths.

More results of the optical tweezers generated within the PANDA ring are as shown in Fig. 4, where in this case the bright soliton is used as the control port signal, and the output optical tweezers of the through and drop ports with different coupling constants are as shown

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in Fig. 4(e) and 4(f), respectively, the coupling coefficients are (1) 0.1, (2) 0.35, (3) 0.6 and (4) 0.75. 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 number of microscopic volume (atom/photon/molecule) can be obtained and seen at the drop/through ports, otherwise, they propagate within a PANDA ring before collapsing/decaying into the waveguide.

In application, the trapped microscopic volumes can transport into the wavelength router via the through port, while the retrieved microscopic volumes are received via the drop port (connecting target), which can perform the drug delivery applications. The advantage of the proposed system is that the transmitter and receiver can be fabricated on-chip and alternatively operated by a single device. Result of the dynamic tweezers with microscopic volumes is as shown in Fig. 5, where the generated wavelengths are 1.4, 1.45, 1.5, 1.55 and 1.6 μm, in which the manipulation of trapped microscopic volumes within the optical tweezers is as shown in Fig. 5(d), where in this case study, the coupling coefficients are given as $\kappa_0 = 0.1$, $\kappa_1 = 0.35$, $\kappa_2 = 0.1$ and $\kappa_3 = 0.2$, respectively.

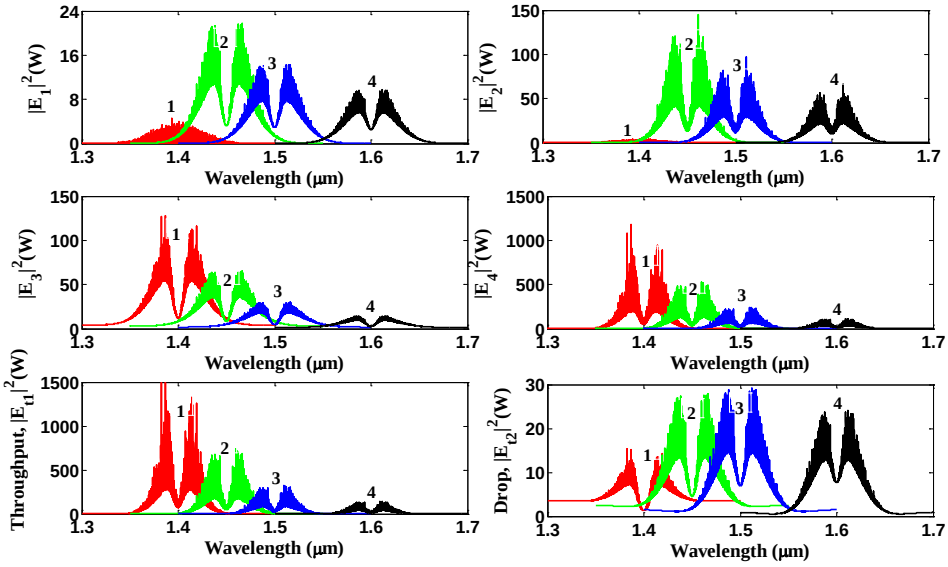

Fig. 4. Simulation result of the tunable and amplified tweezers by varying the coupling coefficients.

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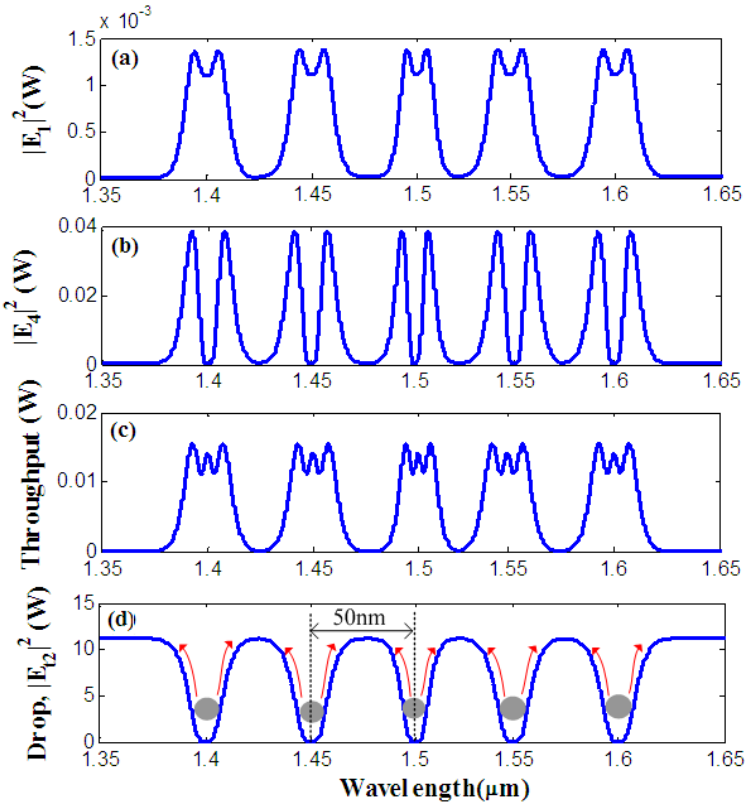

Fig. 5. Result of the dynamic tweezers with microscopic volumes, where the generated wavelengths are 1.4, 1.45, 1.5, 1.55 and 1.6 μm.

4. Conclusion

We have shown that the microscopic volumes can be trapped and transported into the optical waveguide by optical tweezers (vortices). By using a PANDA ring resonator and wavelength router, the long distance drug delivery can be transported and realized. By utilizing the reasonable dark soliton input power, the dynamic tweezers can be controlled and stored within the system. The obtained tweezer spacing with free spectrum range (FSR) of 50 nm is achieved. Moreover, the tweezer amplification is also available by using the nanoring resonators and the modulated signals via the control port as shown in Fig. 4. In conclusion, we have also shown that the use of a transceiver to form the long distance microscopic volume transportation being realized by using the proposed system, in which the drug delivery can be performed via the wavelength router to the required (connecting) targets.

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