Metalens Doublets for Self-sorting of Fluorescent Particles

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Abstract: We establish design principles for, and numerically explore characteristics of, metalens doublets for sorting fluorescent particles in microchannels. The doublets focus fluorescent light back onto the source particles, which may lead to automatic cell sorting.

1. Introduction

Metalens doublet has emerged recently as a promising new approach for metalens-based applications. As opposed to metalens singlets, a metalens doublet uses two distinct metalenses to manipulate light, consequently enabling a higher level of control. An example for this enhanced control is in imaging, where the doublets can suppress aberration at large incident angles and provide a large field of view. Here, we present another potential application of metalens doublet, which is for fluorescence-based particle sorting in microfluidic channels.

Cells and particles are frequently sorted by their fluorescent colors in research labs and clinics, using the technique of FACS (Fluorescence-Activated Cell Sorting). Because of its various drawbacks (e.g. large footprint and high cost), a significant amount of research has been devoted to develop its microfluidic counterpart, μFACS. However, μFACS has yet to replace FACS, and a major reason is that it is not simple enough: the fluorescent light is only a signal, and a sophisticated, often both bulky and expensive sorting mechanism (e.g. a mechanical or electrical system) is still required in μFACS.

In this work, we numerically analyze the electromagnetic properties of a metalens doublet embedded in a microfluidic channel. A distinct feature of the metalens doublet is that, it converts the fluorescent light to the sorting mechanism. This is achieved by focusing the fluorescent light from each cell/particle back onto the source. This focus can generate a self-induced optical trap, which only functions on the source. By cascading identical metalens doublets along the flow direction in a microfluidic channel, a target fluorescent particle can encounter a series of such traps, and the accumulative influence can separate the particle from non-fluorescent particles in space. Comparing to FACS and μFACS, because the embedded metalens doublet eliminates the need of any additional sorting mechanism, the technique can be referred to as FEACS (Fluorescence-Enabled Automatic Cell Sorting), to highlight its self-sorting capability.

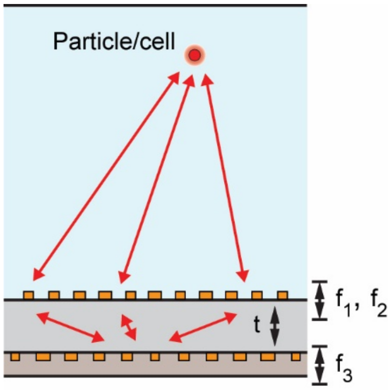

Fig. 1. Schematic illustration of the metalens doublet. The doublet has two layers that are separated by a spacer layer with a thickness of t. f_1, f_2 and f_3 are hyperbolic terms. The arrowed lines indicate that the fluorescent light radiated by the source particle or cell is focused by the doublet back onto the light source.

2. Design principles based on ray tracing matrices

The metalens doublet is designed using ray tracing matrices. In this analysis, the doublet is characterized using a 2×2 matrix M that links the input with the output

$$\begin{bmatrix} r_{out} \\ r'_{out} \end{bmatrix} = M \begin{bmatrix} r_{in} \\ r'_{in} \end{bmatrix} \tag{1}$$

where r_{in} and r'_{in} are the position (with respect to the optical axis) and the slope (the tangent function of the angle formed by the ray and the optical axis) for the incident light, while r_{out} and r'_{out} are the corresponding parameters of the output light. The doublet used here is a stack of two metalenses that share the same optical axis. The top metalens, which faces towards the microchannel, is transmissive and has a focal length of f_a. The bottom metalens is reflective and has a focal length of f_b. They are separated vertically by a distance of t. Converting the transmissive-reflective doublet to a fully transmissive configuration, as required in ray tracing analysis, the corresponding matrix M is

$$M = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_a} & 1 \end{bmatrix} \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_b} & 1 \end{bmatrix} \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_a} & 1 \end{bmatrix} \tag{2}$$

Under the conditions of $f_a = f_1 f_2/(f_1 + f_2)$ (i.e. a lens with two hyperbolic terms), $f_b = f_3$ and $f_2 = -f_3 = t$, the matrix can be simplified to

$$M = \begin{bmatrix} -1 - \frac{3t}{f_1} & 3t \\ \frac{1}{f_1}(2 + \frac{3t}{f_1}) & -1 - \frac{3t}{f_1} \end{bmatrix} \tag{3}$$

Detailed analysis on this matrix leads to two unique characteristics of the metalens doublet: (1) if a fluorescent cell is above the doublet by a distance of f_1, its fluorescent light is always focused back by the doublet onto the cell; (2) if the cell is on-axis and drifts slightly from f_1, the focus moves in the opposite direction, which can restore the height of the cell. These two characteristics can lead to self-induced optical trapping, which can further result in the FEACS technique suggested above.

3. Numerical demonstration of focus tracing

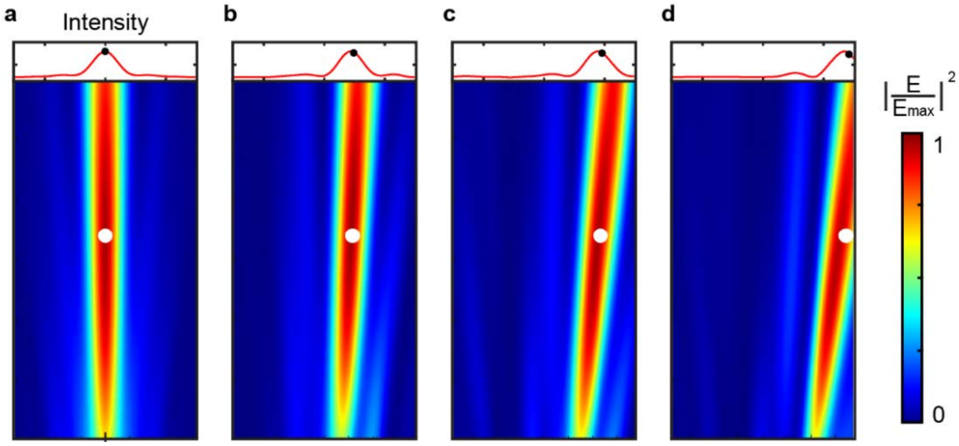

Fig. 2. Movement of focus with that of a source particle in a microfluidic channel. The curves in the top row show the field intensity along a horizontal line across the center of the source particle (white disk), and the field maps in the bottom row show the output electric field intensity of the metalens doublet. The doublet is beneath the bottom of the maps and not visible here. The particle is set to have a diameter of 1 μm. It is on the optical axis in (a), and deviates from the axis by (b) 2 degrees, (c) 4 degrees and (d) 6 degrees.

Figure 2 shows the output of a metalens doublet designed based on the ray tracing analysis discussed above. Both layers of the doublet are a 15 μm × 15 μm hexagonal array of Si nanopillars, and they are separated by a SiO_2 film with a thickness of $t = 20$μm. The top, transmissive metalens has two hyperbolic terms of $f_1 = 71$ μm and $f_2 = 21$ μm, while the bottom, reflective metalens has a single hyperbolic term of $f_3 = -21$ μm. The particle that emits fluorescent light is at a distance of f_3 above the top surface of the doublet. It is modeled as an electric dipole due to its small size (here 1 μm in diameter) with respect to f_3.

Figure 2 compares the output of the metalens at four different particle positions, as the particle moves horizontally from on-axis to the maximum deviation angle of 6 degrees. In all these cases, the doublet produces a clear focus inside the water channel above it. Most importantly, this focus follows the movement of the particle, and the fluorescent particle remains on focus in the whole range of horizontal shift analyzed here. Further simulation on particle displacement in other directions also supports the analysis derived from Eq. (3).