Focusing and Accelerating Light with the Same Flat Lens

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Abstract: We demonstrate how a simple 1D flat lens can be utilized to not only focus light but to generate non-paraxial accelerating beams. We further report how illumination angle and wavelength degrees of freedom allow dynamic transition between these two functionalities.

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Flat optics utilizing metasurfaces and diffractive components has made tremendous advances in the design and realization of compact optical components capable of near arbitrary wave-front control. Among them, flat optical lenses and metalenses have gained particularly significant attention and have matured rapidly in terms of performance and functionality[1]. Separately, metasurfaces with engineered phase profiles have been employed to achieve two dimensional (2D) and three dimensional (3D) accelerating beams, such as finite energy Airy beams and half-Bessel beams[2–4]. These accelerating beams show exotic properties, such as self-healing and the ability to propagate in a quasi-non-diffracting manner around large bending angles. Notably, such accelerating beams open up a novel capabilities in optical systems such as particle manipulation, laser machining, microscopy, and extended depth of field imaging. Here, we report how these two typically distinct functionalities – focusing and accelerating light – can be realized in a simple 1D flat lens[5]. This attractively offers multifunctionality as well as enhanced control over accelerating beam characteristics in a straightforward and compact form factor.

Consider a flat lens with a phase profile $\phi(x)$ that focuses light at a point in z with a focal length of f. At the surface of the lens, we express the transverse wave vector: $k_x = k_2 \sin(\theta_2) = \frac{d\phi}{dx} - k_1 \sin(\theta_1)$. Here, $k = 2\pi n/\lambda$ is at refractive index n, $d\phi/dx$ is the local phase gradient and the angles θ_1 and θ_2 are as shown in Fig 1(a). The unwrapped phase profile is given by: $\phi(x) = -2\pi/\lambda\,(\sqrt{x^2+f^2} - f)$. For on axis illumination ($\theta = 0°$), the imparted phase is defined only by the phase gradient term, and all refracted rays converge constructively to the focus (Fig. 1(b)). However, for off-axis illuminations ($\theta_1 \neq 0°$), the nonzero second term $k_1 \sin(\theta_1)$ shifts the transverse wavevector, and they no longer converge. For $\theta_1 = 6°$, we see an enveloping caustic curve c(z) with a slope of $c'(z)$. Under monochromatic illumination, this results in a constructive interference along a caustic trajectory allowing the formation of a non-paraxial accelerating beam. Fig. 1(c) shows light propagation in fixed $f = 35\mu m$, varying numerical aperture (NA) flat lenses under various illumination angles under a monochromatic (λ=600 nm) light source. Under normal incidence, all lenses in Fig. 1 show diffraction limited focusing. For moderate NA = 0.4, $\theta_1 = 2°$ leads to tilting and shifting of the focal spot. For higher NA of 0.8 or 0.99, however, it produces significant coma and a shape preserving accelerating beam generated along the caustic trajectory in the vicinity of the focal spot. The ~90° bending depicted in Fig. 1(c) for NA = 0.8, $\theta_1 = 6°$ agrees closely with the predicted caustic trajectory in Fig. 1(b). As both the NA and the beam tilt are increased, the bending trajectory is tuned the shape preservation becomes stronger. Modeling was performed with a commercial FDTD solver (Lumerical Inc.) and application of Kirchoff's

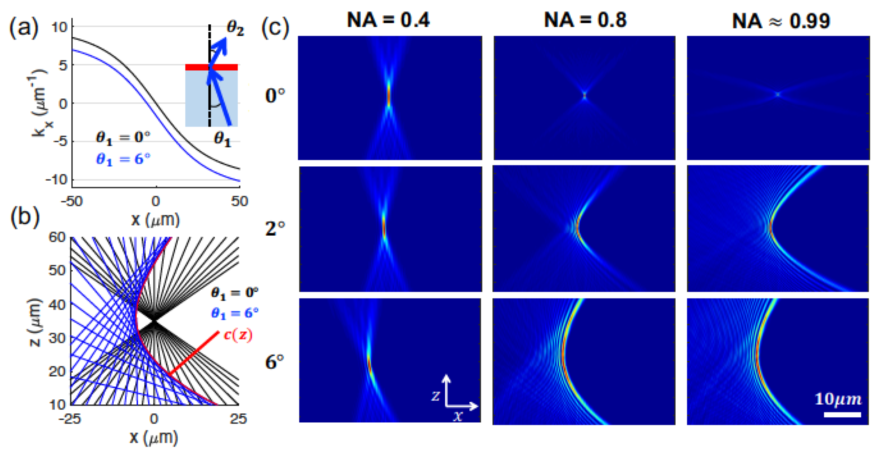

Figure 1 (a) Transverse wavevector vs x for incident angles 0 and 6° (b) Raytracing and caustic curve c(z), (c) simulations showing light propagation for different configurations of NA and incident angle where $f = 35\,\mu m$, $\lambda = 600\,nm$.

integral, where we consider the 1D flat lens as a patterned refractive index metasurface in accordance with our recently developing nanomanufacturing technique[6].

We refer to our particular type of beams as "comatic accelerating beams" (CABs) and they can exhibit sustained shape-preserving qualities around large bending angles similar to Matthieu and Weber beams[7]. However, unlike Matthieu and Weber beams that follow elliptical and parabolic trajectories respectively, the CABs follow hyperbolic trajectories. Importantly this trajectory can be tailored by varying the NA, focal length and tilt angle. It's also possible to achieve such beams under normal incidence with a purposefully engineered phase profile: $\phi_{CAB}(x) = \phi_1(x) + \phi_2(x)$, where $\phi_1(x) = -\frac{2\pi}{\lambda}\left(\sqrt{(x-x_0)^2 + f^2} - f\right)$, denotes a hyperbolic lens designed to focus on or off axis (x_0) while the $\phi_2(x)$ imparts coma (a design tilt) for on axis illumination conditions $\phi_2(x) = x\frac{2\pi}{\lambda}sin(\theta_{tilt})$. Through this approach we've realized the design of long range (~10 mm) hyperbolic trajectory beams under on-axis illumination at $\lambda = 1.31\ \mu m$ with potential applications in optical probing[5, 8].

Lastly, we report a compound multifunctional flat element consisting of a multichromatic lens on the bottom and a phase tilting blazed grating on top where either focusing and/or accelerating beams can be achieved with a wavelength and angle-controlled trajectory. Here, the 1D multi-chrome lens has an NA = 0.8 and an $f = 175\ \mu m$ that suppresses chromatic aberrations for $\lambda = 450$ nm (blue), 524 nm (green) and 635 nm (red). The top layer is a blazed grating that imparts a chromatic phase tilt or a momentum $G = m(2\pi/\Lambda_\mathrm{d})$ to the refracted beam where $m = +1$ is the diffraction order and Λ_d is the grating period. Fig. 3(b) shows that the effect of a non-zero $k_{1,x} = k_1 sin\theta_1$ can be exactly cancelled at a specific design wavelength λ_d where $k_x - G = 0$. As the wavelength is tuned away from λ_d, $(k_x - G)$ can become either positive or negative, and as a result a caustic with either positive or negative curvature can be realized. Figure 3(c) shows such a simulated device with NA = 0.8, f = 175 μm, and G = 4.5 μm^{-1}.

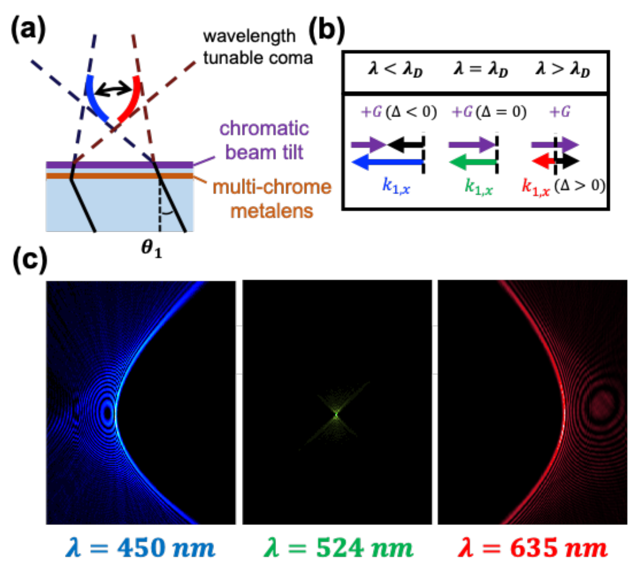

Figure 2. (a) Multifunctional device showing a blazed grating over a multi-chrome flat lens (b) Transverse wavevector k_x after momentum contribution from the incident beam tilt and blazed grating (c) FDTD simulation of the device showing reconfigurable focusing and accelerating of light under $\theta_1 = 15°$.

In summary, we show how a simple 1D flat lens can be used to generate non-paraxial comatic accelerating beams with Airy-like properties. The beam properties are readily tunable via inherent lens design such as NA, focal length, and also by illumination angle and wavelength. The ability to dynamically shift between a focused beam and an accelerating beam offers multifunctionality and enhanced beam control to prospective applications in optical probing, particle manipulation, and laser milling.

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