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An Optical "Janus" Device for Integrated Photonics

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In Roman mythology, the god Janus was depicted with two faces, looking in opposite directions. This led to the phrase ''Janus faced'' which is mostly used for a ''two-faced'' or deceitful character of a person. Within integrated photonics a concept like Janus can provide a new class of multi-functional optical meta-elements which could be a key ingredient in achieving compact and high speed photonic systems. While there have been great strides in the miniaturization of optical elements, such photonic integration largely consists of combining discrete components at the chip level. Here, we present a new approach of designing a single optical element that possesses simultaneously multiple distinct functions. We employ transformation optics to design the optical space and manipulate the light propagation using a metamaterial with spatially varying permittivity. Our experiment demonstrates a single optical ''Janus'' device that acts as a lens as well as a beam-shifter at the same time.

The emerging field of transformation optics has provided a new design methodology allowing an unprecedented manipulation of light propagation, with the optical cloak as the most prominent example.[1,2] However, transformation optics can also be used to enhance the functionality of conventional optical elements. Traditionally, these conventional elements only involve stretching or compressing the optical space in one direction whereas the remaining dimensions in space are unaltered. For example, an optical lens can be interpreted as a result of a simple wavefront transformation that molds the flow of light in a particular direction. A lens works well in one direction whereas light propagating perpendicular to this direction is strongly perturbed. Since space can be modified in two or three dimensions simultaneously, the additional degrees of freedom provided by transformation optics can be used to spatially imprint elements into a single optical Janus or metadevice. Here, we present a transformation optics design approach together with an experimental demonstration that takes advantage of this dimensionality by integrating multiple, independent optical elements into the same footprint.

Electromagnetic waves passing through a physical space can be caused to experience a predetermined virtual space by modifying the underlying material properties in a spatial manner. This is possible because of the invariance of Maxwell's equations[3–5] under a spatial transformation. Therefore, transformation optics opens the possibility to precisely control the flow of light in a medium and thus allow to design novel devices for microwave and optical frequencies such as invisibility cloaks,[6–10] light concentrators,[11–15] beam manipulators,[16–19] object transformers,[20,21] and even electromagnetic wormholes and black-holes.[15,22,23] On the other hand, transformation optics can also be used to improve conventional optical elements. For example, it is possible to transform a Luneberg lens into a lens with flat focal plane without aberration.[24] The flexibility to control the flow of light at will can also be used to design a new class of optical metadevices that can provide different optical functionalities for different light propagation directions.

We demonstrate this capability of transformation optics by imprinting multiple and dissimilar optical functions into one single optical element. This is done by taking advantage of the fact that transformation optics provides a design methodology by which different directions in space can be manipulated independently by employing a well-defined two dimensional permittivity profile. This is in contrast to conventional optical elements which normally alter the phase front only in one propagation direction, without taking advantage of the fact that the refractive index can be engineered for the entire two dimensional space. As an example of a metadevice, we combine a lens with a beam-shifter, acting perpendicular to it, into the same device. Furthermore, we show the flexibility of the transformation optics approach by replacing the lens of the metadevice with a different functionality, in this case, a second beam-shifter. This level of interchangeable dual-functionality cannot be obtained with conventional optical design. Hence, our scheme paves a new way in designing more compact elements in optical integrated circuits.

The two metadevices are designed by reshaping the boundaries (black lines in Fig. 1) of a virtual homogeneous space into a physical inhomogeneous space. The horizontal lens and the vertical shifter (Fig. 1a) are created by the compression of the upper and lower boundaries (which originate from the circumference of the same circle) to flat facets. Due to the fact that rays in the untransformed space must stay perpendicular to the boundaries, the rays have to bend (shown by the dark grey arrows) inside the transformed medium. At the same time, the left and right boundaries are compressed, resulting in a device that can focus a diverging wave into a converging wave, i.e., the element behaves as a lens in the horizontal direction. The same principle

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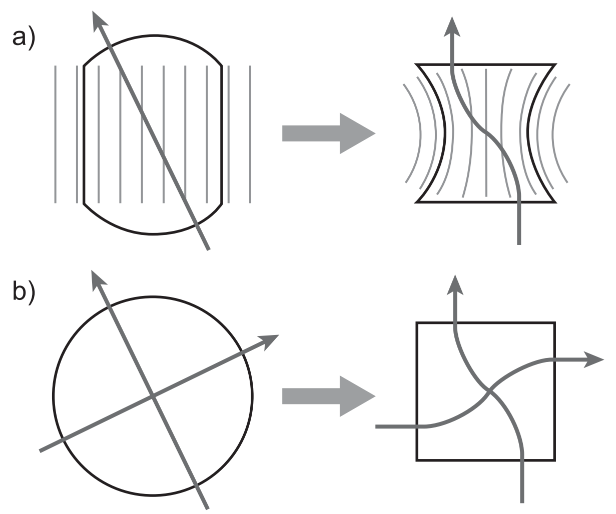

Figure 1. Single step design for obtaining two functionalities by using transformation optics. Two different metadevices consisting of a horizontal lens with a vertical beam-shifter (a) and a beam-shifter for both directions (b). The virtual/physical space is shown in the left/right panel before/after transformation. Only the area inside the black boundary of the physical space is transformed while the area outside is kept unaltered. Dark grey arrows represent the beam directions while the light grey lines symbolize wave fronts.

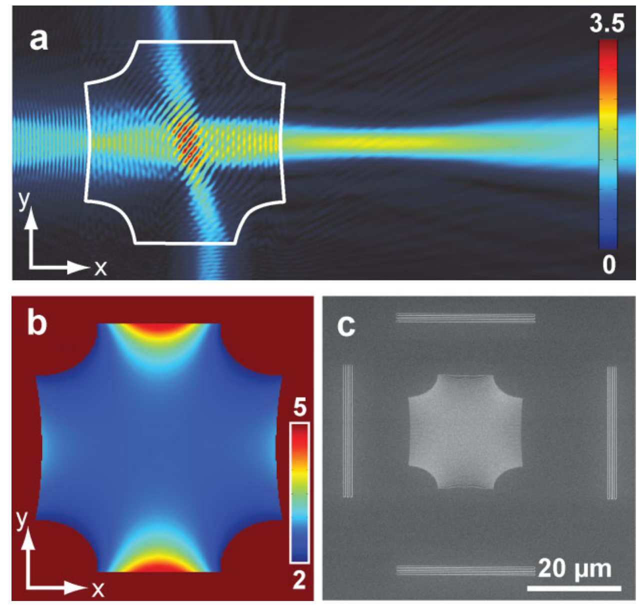

Figure 2. Metadevice consisting of a focusing element (lens) in horizontal (*x*-direction) and a beam-shifter in vertical (*y*-direction). a) Two-dimensional simulation of the spatial electric field magnitude ($|E_z|$) for a large beam propagating in the *x*-direction and a small beam in the *y*-direction. The white line marks the area of the transformed index region. b) Spatial profile for the permittivity obtained by transformation of the space. c) Scanning electron microscope image of the fabricated device together with the grating for coupling light to the transversal magnetic waveguide mode.

is used in the design of the dual beam-shifter as shown in Figure 1b.

Normally, such a transformation would require the use of metamaterials with anisotropic material properties which are in general difficult to realize at optical frequencies. However, here we employ a technique called quasi-conformal mapping[25] which reduces the strong anisotropy of the original transformation. Hence, a nearly isotropic index profile is obtained which can be approximated by the use of isotropic non-resonant dielectric materials. Within the effective material parameter limit such changes can be emulated by a discrete sub-wavelength structuring of the dielectric material.[26] The same approach was successfully used for the first experimental demonstrations of optical cloaking in the NIR.[1,2]

An electromagnetic field plot of a lens/beam-shifter metadevice is shown in Figure 2a. A beam passing the device in the *x*-direction will be focused 10 μm from the opposite side of the element, whereas a beam propagating in *y*-direction will be shifted by 10 μm when passing through the element. We experimentally demonstrate the optical metadevices using a silicon-on-insulator (SOI) substrate, allowing a straightforward implementation into standard complementary metal–oxide–semiconductor (CMOS) platforms. Such an implementation of transformation optics can bring together the advantages of fast and low loss photonic elements with the superior and highly integrated electronic properties of semiconductor materials like silicon.[27–29] Our devices are realized within the silicon slab waveguide of the SOI by spatially varying the effective refractive index profile for the transverse-magnetic (TM) optical waveguide mode. Each metadevice is transformed from a background region in the silicon waveguide by taking the dispersion of the TM waveguide mode into account. For the metadevice shown in Figure 2 the theoretical permittivity profile of the element was translated into a pattern of 75 nm air holes ($\varepsilon = 1$) with a spatially dependent density. This approach allows us to cover an effective permittivity range from 2 to 5 for the TM waveguide mode in a 250-nm-thick silicon slab. Although the approximation of the permittivity profile with a discrete pattern can lead to scattering loss and reflection from the device boundary, the overall functionality is preserved.

In addition to the hole pattern for the metadevice, four grating couplers are fabricated where a typical geometry for the total structure is shown as an scanning electron microscopy (SEM) image in Figure 2c. The gratings are designed to launch a TM mode at 1500 nm into the waveguide. However, the finite size of the gratings provides a coupling range over a wide frequency band in the NIR and can be used with slightly lower efficiency for different wavelengths. For the experiment, we utilize the grating coupler not only for launching the light into the waveguide but probing the beam position and shape after passing the element.

A close up SEM image of the fabricated metadevice lens (*x*-direction)/shifter (*y*-direction) device is shown in Figure 3a. Excitation of the TM waveguide mode, which passes the lens in the *x*-direction, is performed using a Gaussian beam profile with a spot diameter of 13 μm at the input grating, whereas a small beam spot with a diameter of 2 μm is used for the beam-shifter in the *y*-direction. It can be seen in Figure 3b that the wide beam size is strongly reduced after passing the metadevice in *x*-direction. Conversely, if the beam is propagating in the perpendicular direction through the device it is shifted at the output grating from left to right and vice versa (Fig. 3c).

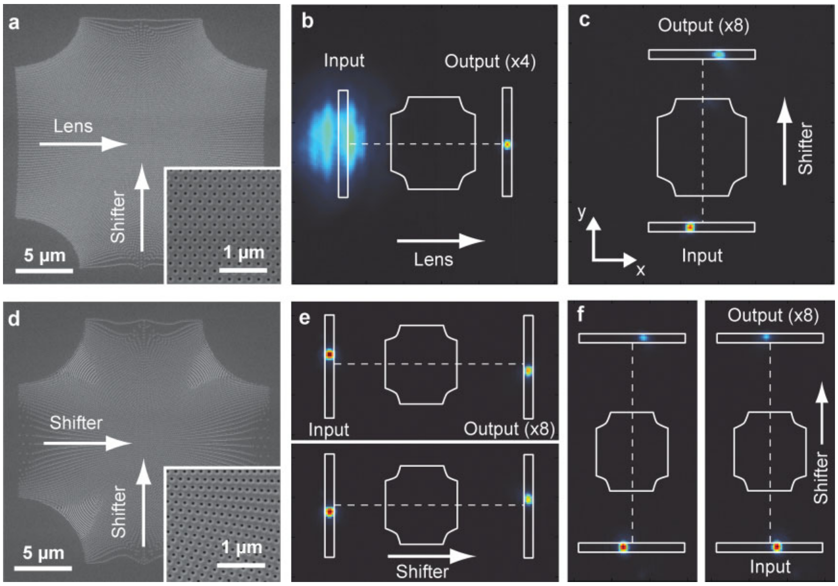

Figure 3. Metadevice performance at a wavelength of 1500 nm. Combination of (a–c) a lens and a beam-shifter and (d–f) two beam-shifter elements. a,d) Scanning electron microscope images of both devices. The footprint for both devices is 22 μm × 22 μm. The inset shows a magnified view of the air holes in the silicon waveguide slab with a hole diameter of 75 nm. b,c) Optical microscope images with the intensity distribution at the in-couple and out-couple gratings for the lens (horizontal) and the shifter (vertical). Due to the strong back reflection of the excitation beam from the silicon surface the intensities of the output profiles are scaled by 4 times and 8 times, respectively. The white boxes mark the position of the gratings and the hole pattern for the metadevices. e,f) Optical microscope images for the dual-shifter device.

Using transformation optics as the design methodology not only provides the possibility to incorporate very different functions into a single optical element, but it also allows replacing functionalities without influencing the perpendicular propagation direction. Such a design becomes possible because each device demonstrated here utilizes a transformation that only alters part of the original virtual space boundary (Fig. 1). We demonstrate this possibility by replacing the focusing element with a second beam-shifter for the x-direction. Figure 3d shows the SEM image of the fabricated pattern for such a dual-shifter metadevice. The device uses the same etched hole size as the lens/shifter element to realize the designed refractive index profile. Both directions of the metadevice act now as a beam-shifter for the x- and y-direction as can be seen from the optical microscope images (Fig. 3e–f). The overall footprint size is identical for both devices which allows them to be interchangeably used in modular on-chip designs. However, the shape of the device's footprint can be arbitrarily designed by transformation optics which allows for efficient and flexible integration into specific architectures.

A more detailed analysis of the metadevice consisting of the lens and the beam-shifter is shown in Figure 4. To probe the beam propagation characteristics for the focusing element, out-coupling gratings were fabricated at various distances from the center of the structure and the beam profile was measured at these locations. The results are shown in Figure 4b in comparison to the beam profile measured in the absence of the metadevice. By fitting a Gaussian profile to the experimental beam shapes the size of the beam in the focal region was extracted and compared to the values obtained from the numerical calculation (Fig. 4c). We obtain a reasonable agreement in a spot size of approximately 2 μm which represents a reduction of the original beam size by more than a factor of six.

In addition to the focusing element of the metadevice, we investigated the performance of the beam-shifter for different positions of the input beam. The beam-shifter is designed to shift a beam perpendicular to its propagation direction without changing its shape and size when passing the device (see Fig. 2a). The preservation of the beam shape within the device is inherent to the particular transformation. The maximum beam shift of 10 μm is obtained when the beam enters the device close to the corners of the pattern whereas it is shifted to the opposite corner at the output side of the element. A detailed analysis can be found in the Supporting Information.

Since the index profile for the element is made purely from dielectric materials, and does not include resonant metamaterials with metal inclusions, the structures are relatively low loss and potentially broad band. For the 2 μm input spot size we measure 78% transmission which includes the reflection loss of ∼10% from the element boundaries. However, with additional optimization of the element size for a certain beam size and index

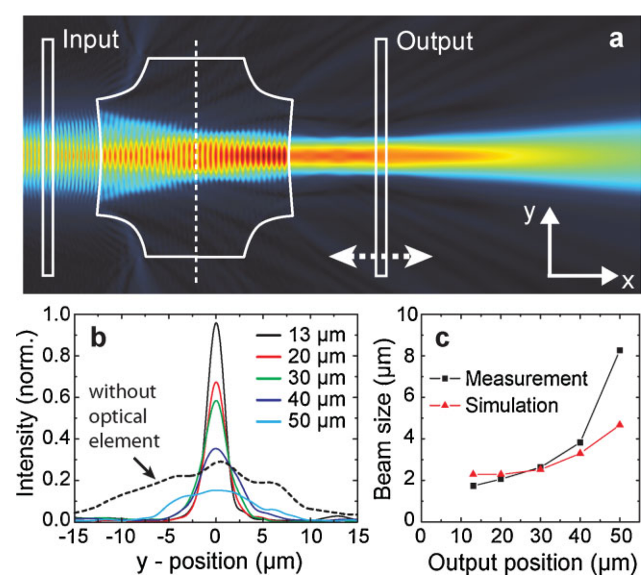

Figure 4. Metadevice consisting of a lens and a beam-shifter. a) Magnitude of the electric field ($|E_z|$) for a 13 μm wide beam traveling from left to right through the focusing element. b) Measured beam intensity profiles for different distances of the output grating from the center of the device for $\lambda = 1500$ nm. The dotted black line corresponds to a measurement without the optical element between the gratings. The intensities are normalized with respect to the profile for 13 μm distance. c) Retrieved spot size from the measurements (black) compared to the design values extracted from the simulation (red).

matching the device boundaries to the silicon, the scattering losses can be further reduced. In addition, the measurement of the shifting performance for several wavelengths shows that the element works over a range of 100 nm for a center wavelength of 1500 nm.

In conclusion, we have experimentally demonstrated that transformation optics can provide a new route for designing and integrating multiple optical functions into a single element. To make optical elements economically feasible for smart integrated devices, they have to be comparable in size to conventional electronic components and compatible with standard semiconductor fabrication technologies. Although, there has been tremendous progress in integrated photonics to enable light propagation on a wavelength scale,[30] the footprint of many functional optical devices is still very large compared to their electronic counterparts. Furthermore, the miniaturization of optical elements will be ultimately limited by the diffraction limit of the light which is on the order of the wavelength. Transformation optics can help to overcome this scaling limitation by integrating multiple optical elements into one footprint while preserving their independent functionalities. This type of ''Janus'' devices opens a new avenue to achieve a high density of functionality, effectively scaling down the size of photonic systems.

Experimental

The metadevice was fabricated in a 250-nm-thick crystalline silicon device layer of an SOI wafer (Soitec). The device layer spaced by a 3-μm-thick silicon oxide layer from the silicon substrate. A poly methyl-methacrylate (PMMA) resist layer is spun onto the SOI wafer and electron beam lithography is used to expose the hole pattern into the resist. The metadevices consist of roughly 15 000 holes with a diameter of 75 nm, placed in a 22 μm $\times$ 22 μm area with varying density. After development with methyl isobutyl ketone (MIBK), the hole pattern is etched through the underlying silicon device layer using a reactive ion transformer coupled plasma etcher with Cl_2, HBr, and O_2 as process gases (Lam Research TCP 9400). Finally, the PMMA resist mask is removed via a short oxygen plasma etch. For all optical experiments the light from an optical parametric oscillator (OPAL SpectraPhysics) is focused with a 50 $\times$ /NA 0.4 near-infrared microscope objective lens. The scattered light from the surface is imaged with the same objective lens to an indium-gallium-arsenide array detector.

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