Transformation Optics on a Silicon Platform

CNF Project # 980-01
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Abstract:

Transformation Optics (TO) is a tool for design of innovative devices. Nonetheless, its implementation in optical frequencies remains a challenge. The use of solely dielectric materials and non-resonant structures is desirable in the optical domain to guarantee operation in a broad range of wavelengths. In this report, we discuss our advances in fabrication methods employed to create TO devices using silicon-on-insulator (SOI) as our dielectric platform.

Summary of Research:

Transformation Optics shows that spatial geometry and the constitutive parameters of materials affect electromagnetic waves in the same manner [1,2], allowing the implementation of virtual geometries in real space, via gradient refractive index (GRIN) media.

The fabrication of GRIN media is common in fiber optics, where the amount of dopants in the glass can be well controlled, and, in turn, determines the refractive index of the glass. However, this allows no more than a few percent variation in refractive index, while requirements for TO devices can easily reach index contrasts of 2:1 and more. By using a silicon platform, we are able to work with higher refractive index contrasts (nSi = 3.5) and operate at wavelengths around 1550 nm.

We use SOI wafers to fabricate the structures, so that light is confined in a high index layer, surrounded by low index media. If the final devices are large enough to approximate adiabatic index variations, we can decouple the vertical confinement in the guiding layer and the wave propagation in the plane. In this case, the index we need to control is the effective index in the propagation direction only. Looking at the guiding structure, a layer of thickness t and index n surrounded by lower index media, we note that, if the surrounding media is kept constant, we can change either n or t to control the propagation constant.

The guiding layer index can be changed through effective medium theory. The result of mixing sub-wavelength regions of high and low indexes is an effective index that is proportional to the volumetric fraction of each component [3,4]. In our platform, mixing sub-wavelength silicon pillars with air-filled regions, allows us to reach index contrasts a little over 2:1. The fabrication of such structures can be achieved via high-resolution e-beam lithography and anisotropic etching. The downside of this technique is that the resulting structure presents high scattering losses. In our experiments, we were able to achieve silicon pillars with diameters down to 60 nm with precise positioning.
fundamental to control the local fractions of silicon and air. Figure 1 shows a scanning electron microscope (SEM) image of a device fabricated using electron-beam lithography and inductively coupled plasma, reactive ion etching on silicon: a Maxwell fish eye lens [5].

The other alternative, changing the thickness of the guiding layer, can be implemented by different methods. Using a calibrated focused ion beam (FIB), we can sculpt the design into the silicon layer in a one-step process. However, the FIB will implant ions in this layer, as well as break its crystalline structure to some extent, both of which will increase propagation losses. Surface roughness introduced by the FIB is not a major concern, since it can be held below 2 nm RMS.

Another possible method for controlling the thickness of the silicon slab is gray scale lithography [6], with its own advantages and disadvantages. We fabricated the Maxwell fish eye lens using the FIB method, and achieved minimal error with respect to the design in a very repeatable fashion. Figure 2 shows an atomic force microscope (AFM) scan of the lens, and Figure 3 compares a cross-section of this scan with the designed profile. We can see that the surface roughness is minimal, at the same time that the thickness control is very precise.

Using only dielectrics and non-resonant structures for TO devices guarantees a broad wavelength range of operation. This report briefly discusses our advances in the fabrication processes that will allow TO devices to fulfill their potential in fundamental areas such as invisibility, imaging, and solar power collection.

References: