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3D Non-Resonant-Inclusion IR Metamaterials

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Abstract

Membrane projection lithography (MPL) is a fabrication approach capable of creating submicron-scale metamaterial structures. Here MPL is combined with interferometric lithography (IL) to create IR metamaterials with non-resonant inclusions. Furthermore, we use standard contact lithography to create device structures such as waveguides and interferometers with varying in-plane permittivity controlled by the density and size of the metallic inclusions created using IL.

1. Introduction

As the field of metamaterials continues to advance, the palette of proposed sub-wavelength structures used to manipulate the electromagnetic properties of the metamaterial continues to expand. While considerable work is still aimed at “classic” resonant metamaterial inclusions such as split ring resonators (SRRs), an area of increased interest is the use of deeply sub-wavelength off-resonance metallic inclusions to boost the local permittivity of the medium in pursuit of all-permittivity optical designs generated through transformation optics [1]. By operating off-resonance, ohmic dissipation in the metal is drastically reduced. The fabrication of both resonant and non-resonant metamaterial inclusions which operate at optical wavelengths continues to be a significant challenge. This paper reports our recent progress in combining interferometric lithography (IL) with membrane projection lithography (MPL) as a fabrication method to create metamaterials with non-resonant metallic inclusions for spatially varying permittivity applications in the IR wavelength range. Furthermore, we extend the technique, combining contact lithography with interferometric lithography to create materials with in-plane variation in the density of metallic inclusions, paving the way for devices with inhomogeneous and/or spatially graded in-plane permittivity.

2. Fabrication

The basic premise of MPL is to create a patterned membrane suspended over a cavity which represents the metamaterial unit cell. Directional evaporation through the membrane deposits replicas of the membrane pattern on the interior face(s) of the cavity. In MPL, cavity shape, unit cell geometry, membrane pattern, number and angle of evaporation(s), and resonator material can all be adjusted to optimize the performance of the resulting metamaterial [2,3]. While we use e-beam lithography to define resonant inclusions such as SRRs, one advantage of using non-resonant metallic inclusions is that the local permittivity is largely insensitive to the shape of the metallic inclusion, being controlled instead by the fill fraction of metal. This allows us to use scalable, large-area patterning techniques, such as interferometric lithography, to pattern the membrane with deeply sub-wavelength metallic dots rather than intricate patterns such as SRRs.

In interferometric lithography, the interference pattern generated by overlapping mutually coherent plane waves is used to expose photoreisist. To combine IL with MPL we first create a 2-D array of unit cells in SU-8, then backfill and planarize with a developable polyimide. After planarization, negative tone photoresist (PR) is spin-deposited and exposed using the tripled (355nm) line from Q-

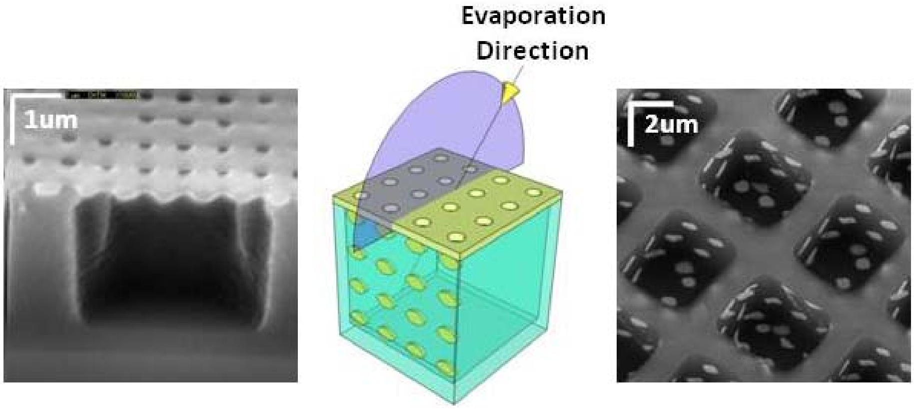

Fig. 1: (Left) SEM image of an interferometric lithography patterned membrane suspended over a cubic unit cell cavity. (Center) Schematic of a single directional evaporation through a photoresist membrane patterned with IL. (Right) SEM image of cubic unit cells decorated with sub-wavelength dots after 5 direction evaporations.

switched Nd:YAG laser. Development of the PR results in dissolution of the underlying polyimide and creation of a perforated PR membrane suspended over the SU-8 cavity (Fig. 1: left). Directional evaporation through the perforated membrane (Fig. 1: center) and liftoff yield the final metal-decorated unit cell with sub-wavelength metallic dots (Fig. 1: right). The density and size of the inclusions can be controlled by adjusting the geometrical parameters (number and angles of interfering beams) of the IL exposure. IL is capable of patterning these sub-wavelength perforations in ~20 seconds covering many cm^2 in a single exposure, making it much faster than e-beam lithography for simple periodic patterns.

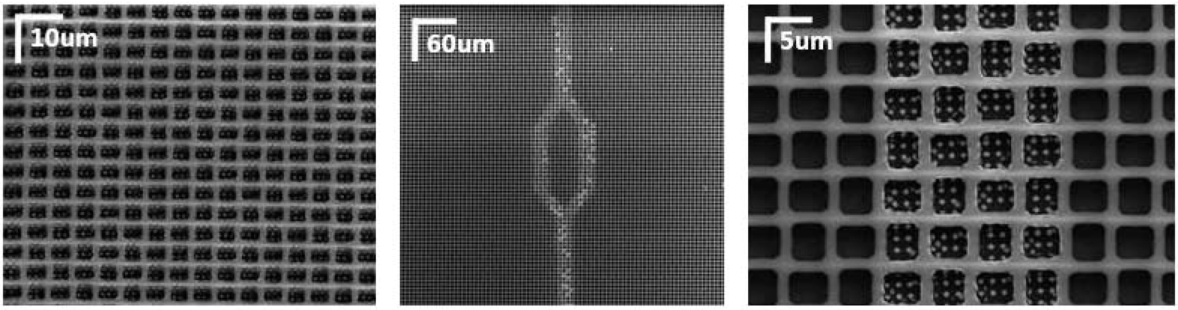

Fig. 2: (Left) Low magnification SEM image of a spatially homogenous material with metallic inclusions uniformly decorating the entire film. (Center) Low magnification SEM image of a waveguide and Mach-Zender interferometer formed by material with metallic inclusions while the balance of the material is undecorated. (Right) Higher magnification SEM showing the decorated and undecorated regions in detail.

Fig. 2: (left) contains a low magnification SEM image of a large area patterned with ~300 nm metallic inclusions created with IL. A powerful feature of this approach is that the deep sub-wavelength, high spatial frequency inclusions provided by IL can be combined with contact lithography to create inhomogeneity in the in-plane permittivity of the material. Fig. 2: (center) shows a prototype waveguide with a Mach-Zender interferometer created by exposing the membrane using IL followed by a subsequent contact exposure prior to developing. After post exposure bake, the doubly exposed membrane is then developed, yielding a perforated membrane only in the areas where the waveguide is required, and a solid membrane elsewhere. The bright regions visible in the waveguide of Fig. 2: (center) are lift-off related defects, which can be eliminated with optimized exposure/bake parameters. Fig. 2:

(right) contains a higher magnification SEM image showing high contrast between the decorated boxes of the waveguide and the surrounding undecorated boxes of the "cladding."

3. Modeling

Fig. 3: contains a plot of the extracted refractive indices for a periodic array of air-filled SU-8 boxes with varying different sized metal (Au) patches on their interior faces. Rigorous coupled wave analysis (RCWA) was used to compute the transmitted and reflected complex field amplitudes which were then

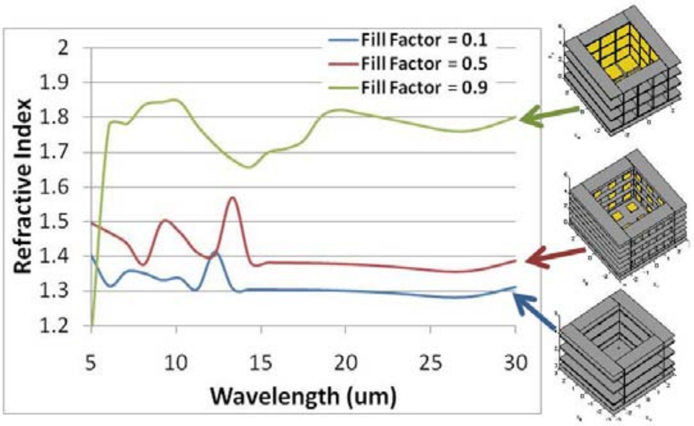

Fig. 3: Plot of extracted index of refraction from RCWA simulations of air-filled cubic SU-8 unit cells with varying metallic inclusion interior face coverage fill fraction.

used in a standard extraction algorithm [4] to arrive at the plotted index of refraction. It is apparent from the simulations that increasing the interior face coverage fill factor inside the unit cell offers a route to increasing the effective index of the sample.

4. Conclusion

We show that membrane projection lithography can be combined with interferometric and contact lithography to create structures with varying in-plane spatial permittivity profiles such as waveguides and interferometers. We are currently optically characterizing these structures. The local permittivity can be controlled by varying the exposure parameters of the interferometric lithography step which adjusts the density and size of the metallic inclusions in a straightforward fashion. This technique is scalable to large areas, as it replaces serial e-beam writing with a single ~20 second IL exposure and a single ~5 second contact lithography exposure to cover many cm^2. The combination of MPL with interferometric lithography shows great potential as a technique to create next generation integrated optical devices shown here as well as an ideal platform for realizing more complex optical components designed using transformation optics [1].

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