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Experimental demonstration of a broadband array of invisibility cloaks in the visible frequency range

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Abstract. Very recently Farhat \textit{et al} (2011, \textit{Phys. Rev. B} 84 235105) suggested that arrays of invisibility cloaks may find important applications in low-interference communication, noninvasive probing, sensing and communication networks and so on. We report on the first experimental realization of such an array of broadband invisibility cloaks that operates in the visible frequency range. The wavelength and angular dependences of the cloak array performance have been studied.

Ever since the first experimental demonstrations in the microwave [2] and visible [3] ranges, invisibility cloaks have stimulated considerable progress in the fields of metamaterials and transformation optics [4–7]. Based on the considerable recent progress in cloaking research, Farhat \textit{et al} [1] very recently introduced the new concept of an invisibility cloak array, which they suggest may find applications in such fields as low-interference communication, noninvasive probing, sensing and communication networks and so on. Besides these potential practical applications, building and studying the arrays of invisibility cloaks offers more refined experimental tools for testing cloak performance. Here we report on the first experimental realization of such an array of broadband invisibility cloaks that operates in the visible frequency range. Our experiments reveal interesting coupling effects between neighboring cloaks, which have not been explored previously.

Our experimental geometry is based on the two-dimensional (2D) broadband invisibility cloak design, which utilizes an adiabatically tapered gold-coated waveguide that emulates the anisotropic dielectric permittivity and magnetic permeability distributions required for

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realization of the transformation-optics-based invisibility cloak [8] (see figure 1(a)). This approach leads to low-loss, broadband performance in the visible frequency range, which is difficult to achieve by other means. This simple design has been extended to 3D cylindrical geometry and its broadband performance was independently verified in 3D [9]. The basic idea of this design may be easily understood using the ray-optics approximation based on the semi-classical 2D cloaking Hamiltonian (dispersion law) introduced in [10]:

$$\frac{\omega^2}{c^2} = k_r^2 + \frac{k_\psi^2}{(r-b)^2} = k_r^2 + k_\psi^2 \frac{b (2r-b)}{r^2 (r-b)^2 r^2}. \quad (1)$$
Figure 2. Light propagation through a rectangular cloak array formed by the gap between the gold-coated surfaces of a large microlens array (500 μm pitch, 56 mm lens radius) and a flat glass slide. (a) Microscope image of the gold-coated lens array. (b) Microscope image of 514 nm light propagation through the cloak array. Dashed line indicates the waveguide edge. Light propagation direction is indicated by the arrow. (c) Magnified image of 514 nm light propagation through the cloak array. Similar to [8], cloaked areas appear as dark circles surrounded by concentric rings.

Jacob and Narimanov [10] demonstrated that for such a cylindrically symmetric Hamiltonian, the rays of light would flow smoothly without scattering around a cylindrical cloaked region of radius $b$. Such a cloaking Hamiltonian may be emulated by a gold-coated tapered waveguide, which thickness $d$ in the $z$-direction changes adiabatically with radius $r$. The dispersion law (Hamiltonian) of light in such a waveguide is

$$\frac{\omega^2}{c^2} = k_r^2 + \frac{k_x^2}{r^2} + \frac{\pi^2 m^2}{d(r)^2},$$

where $m$ is the transverse mode number. It appears that the cloaking Hamiltonian (1) can be emulated by an adiabatically changing $d(r)$. Moreover, the required waveguide shape is very close to a gap between a sphere and a plane surface [8]. The cloak radius for a mode number $m$ is then given as

$$r_m = \sqrt{(m + 1/2)R\lambda},$$

where $R$ is the sphere radius and $\lambda$ is the wavelength of light. Thus, the cloaking areas should be different at different light wavelengths, which has been verified experimentally in [11]. This cloaking geometry appears to be broadband, with the cloaked areas for different light wavelengths nested inside each other [8, 11]. As demonstrated in figure 1(a), the geometry described is easy to transform into an array of broadband invisibility cloaks using commercially available microlens arrays. In the ideal case scenario light would propagate through such an array without scattering, as demonstrated in figure 1(b).

Our invisibility cloak arrays were fabricated as follows. As a first fabrication step, a commercially available microlens array\(^4\) was coated on the microlens side with a 30 nm gold film (figure 2(a)). The array was placed with the gold-coated side facing down on top of a flat glass slide coated with a 70 nm gold film. Two gold-coated surfaces were pressed against each other using a mechanical arrangement with set screws. Argon ion laser light with different

\(^4\) http://www.suss-microoptics.com
Figure 4. The broadband performance of the cloak array is illustrated by two images of light propagation through the array taken using 514 nm (a) and 488 nm (b) laser light coupled into the waveguide from the side. Image (c) was taken using a combination of illumination with white light from the top and 514 nm laser light from the side and further illustrates that laser light travels around the central Newton ring areas of the cloaks, which appear bright under the white-light illumination from the top.

wavelengths $\lambda$ was coupled into the waveguide from the side. A periodic array of adiabatically tapered gaps between the gold-coated surfaces was used as a 2D array of invisibility cloaks similar to those described in [8, 9].

As a first experimental step, we studied 514 nm light propagation through a cloak array formed by an array of large microlenses (500 µm pitch, 56 mm lens radius), as shown in figure 2. As is clearly visible in figure 2(b), the laser beam diameter in this experiment is comparable to the distance between the individual cloaks in the array. The dashed line in figure 2(b) indicates the waveguide edge (the top and bottom gold-coated surfaces did not overlap precisely), while the light propagation direction is indicated by the arrow. Similar to [8], cloaked areas appear as dark circles surrounded by concentric rings in the experimental images. According to equation (3), roughly 20% of the surface area is cloaked in this experiment, which is consistent with the experimental image in figure 2(c). While such images clearly demonstrate that an array of cloaks has been created in the experiment, cloak separation appears to be too large to study individual cloak interaction.

In order to clearly demonstrate the effects of cloak interaction, we used smaller array parameters (30 µm pitch, 42 µm lens radius) in the next set of experiments. These results are presented in figures 3–5. From basic symmetry considerations, the hexagonal dense cloak array shown in these figures is supposed to work best while illuminated along its three main symmetry axes, as shown in figure 3. Indeed, the microscope image of 514 nm light propagation through the cloak array is consistent with the ‘idealized’ cloaking behavior, as shown in the inset. Similar to [8], cloaked areas appear as dark circles. The inset in figure 3(b) illustrates light propagation through the array. We were also able to confirm broadband cloaking behavior for the cloak array illuminated along one of the main symmetry axes. Images of the array taken using 514 nm (figure 4(a)) and 488 nm (figure 4(b)) laser light coupled into the waveguide from the side illustrate similar cloaking performance.

However, the angular performance of the dense hexagonal cloak array clearly shows signs of deterioration. As illustrated in figure 5(d), cloak array illumination along the direction that does not coincide with one of the three main symmetry axes of the array leads to a reduction
Figure 5. Light propagation through the rotated cloak array indicates reduction in cloak array performance. Image (a) was taken at 514 nm when the cloak array was rotated by $\sim 90^\circ$. The orientation of the cloak array is demonstrated in image (b), using a combination of white-light illumination from the top and 514 nm laser light from the side. Comparison of images (a) and (c) clearly demonstrates enhanced scattering inside the rotated cloak array. This result may be explained by the reduced symmetry of the problem, as illustrated in (d), where the direction of light propagation does not coincide with one of the three main symmetry axes of the hexagonal array.

of the symmetry of the problem. This must lead to enhanced light scattering inside the array. Comparison of images in figures 5(a) and (c) does indeed demonstrate such an enhanced light scattering inside the rotated cloak array. The deterioration in the angular performance of the array comes has two main causes: deviation of the individual cloak shape from the ideal profile required for cloaking [8] and the inevitable breakdown of adiabatic approximation when individual cloaks are too close to each other.

In conclusion, we have reported the first experimental realization of an array of broadband invisibility cloaks that operates in the visible frequency range. Such an array is capable of cloaking $\sim 20\%$ of an unlimited surface area. We have studied the wavelength and angular dependences of the cloak array performance. While the broadband performance appears to be similar to the performance of individual cloaks in the array, the angular performance of a dense array shows signs of deterioration due to a reduction of the symmetry of the cloaking arrangement.

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