Toward Engineering 2D Atomic Arrays in Solids

Trevor Kling[1], Haechan An[3], Mahdi Hosseini[1,2,3]

1. Applied Physics, Northwestern University, Evanston, IL 60208
2. Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL 60208
3. Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907
mh@northwestern.edu

***Abstract*—Here we present an atomic spiral diffractive element for the focusing, reflection, and directional scattering of light. We demonstrate how such a system imprints an angular momentum in its scattered light and discuss the implications of realizing such a system in solid-state photonics.**

Keywords—passive optical elements, collective behavior, light-matter interactions

I. Introduction

Diffractive optical elements are of great interest in both theory and application of photonics. Concentric rings of opaque and transparent materials, known as a Fresnel zone plate, allow for the focusing of light over a wide range of frequencies. These rings can also be replaced by a corresponding lattice of pinholes, known as a photon sieve, to improve the spot size of the resulting foci [1]. Additionally, the properties of the focused light can be tailored by modifying the geometry and optical properties of the diffractive element. Spiral-shaped elements have been shown to impart an angular momentum to the focused light, resulting in a phase singularity at the center of the beam [2].

In recent years, there has been growing interest in diffractive elements composed of individual atoms. A lattice of atoms can perform as a highly reflective mirror in a 2D array [3-4], employing the dipole-dipole interactions to enhance reflectivity. The resulting subradiant response allows for the formation of atomically thin optical elements.

Previously, our group has investigated the effect of atomic geometry on light-matter interactions in 1D structures. Rare-earth doped crystals were optically excited with a standing-wave pump, and the resulting periodic spatial distribution demonstrated coherent reflection [5]. We additionally investigated the behavior of ions implanted in 1D nanostructures; an array of resonantly-spaced thulium ions implanted in a lithium niobate micro-ring resonator exhibited long-range coupling and superradiance signatures [6]. We also investigated the details of the collective behavior of these micro-ring arrays, showing that the atom-resonator coupling applies limitations to the scalability of such arrays [7]. Now, we turn our attention to two dimensional atomic arrays with greater freedom in waveguide-free atom-atom interaction design.

Here, we design a Fresnel-type optical diffractive element of a lattice of rare-earth ions implanted in a solid-state medium. The proposed system consists of a spiral of thulium ions implanted in a lithium niobate substrate. The geometry of the spiral can be chosen to modify the focal length and hollow beam radius, while the interatomic spacing within the spiral determines the reflectivity of the array. Additionally, we discuss the influence of a solid-state environment on the operation of these systems. We hope to expand upon the understanding of the behavior of these arrays in solid-state, with the goal of reaching a controllable strong light-atom coupling regime.

II. Design and Simulation

When designing an atomic reflective element, the dipole-mediated collective effects enhance the reflective properties of the array for geometries with spacing less than a singular wavelength [3]. However, in a traditional Fresnel zone plate design, the geometric requirements for the spacings of the rings limits the total collective behavior of the atoms. By replacing the individual rings with a single-arm spiral, the atoms can be spaced within the spiral to maximize the collective effects without compromising the focusing properties of the system. In this design, the atoms within the array take the place of the pinholes used in a traditional photon sieve.

Just as with the examples of a zone plate, a spiral atomic lattice imparts an angular momentum to the reflected and focused light. This can be seen most clearly through the interference patterns calculated in Figure 1. The standing-wave pattern seen in the XZ plane cross-section demonstrates an asymmetry across the z-axis, indicating the winding of the phase of the reflected light. Here segments are spaced by 0.4 wavelengths λ; the system displays improved focusing properties for arrays with a spacing between 0.3λ and 0.8λ. Atoms are excited by an incident Gaussian beam with waist size comparable to the diameter of the spiral, uniformly polarized in the x-direction with amplitude E_{in}. The influence of collective behavior on the atoms in the reflector can be seen in Figure 2. The dipole-dipole interactions produce a spacing-dependent phase shift and modification to the atomic linewidth.

III. Solid-State Effects

In a solid-state system, reflections from the surface of the material can additionally induce phase shifts in the atomic ensemble. To avoid these effects dominating the behavior of the reflector, the atoms must be implanted at a depth greater than the spacing of the lattice. To accomplish this, we implant our ions first at a depth of 50 nanometers via a focused ion beam. The host materials considered include lithium niobate and silicon

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nitride; in both cases a top cladding of titanium dioxide or silicon nitride, respectively, can be added after implantation.

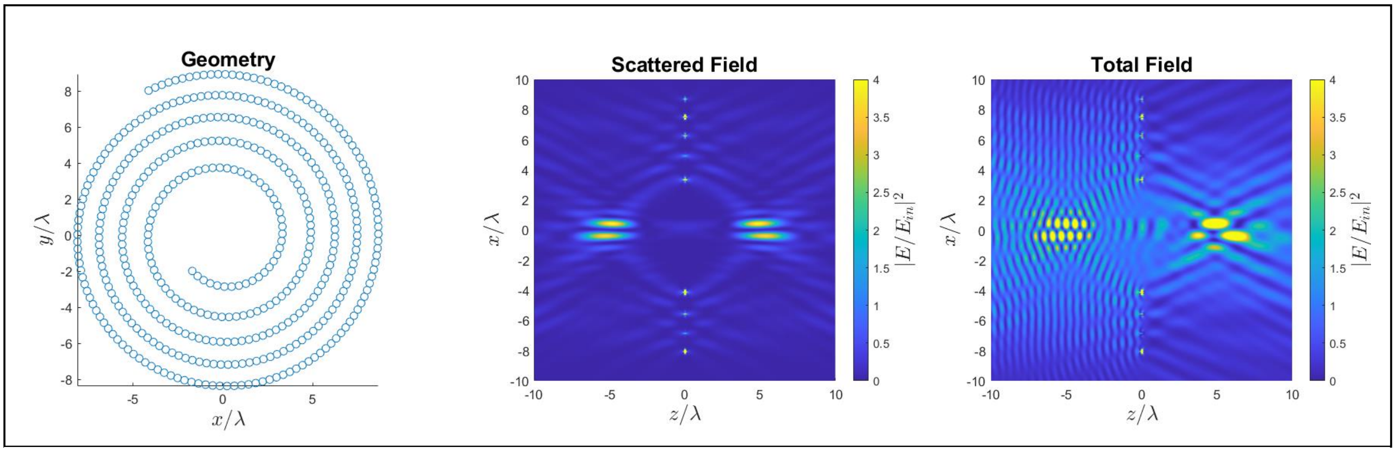

Fig. 1. Simulated geometry and spatial intensity plots for a spiral of 450 atoms. For simulation clarity, the focal length of the pattern is chosen to be five wavelengths. The system is illuminated by a Gaussian beam incident along the positive z-axis, for the case of an atomic spacing equal to 0.4 wavelengths along the spiral arm. The scattered field and interference pattern are normalized to the incident field amplitude.

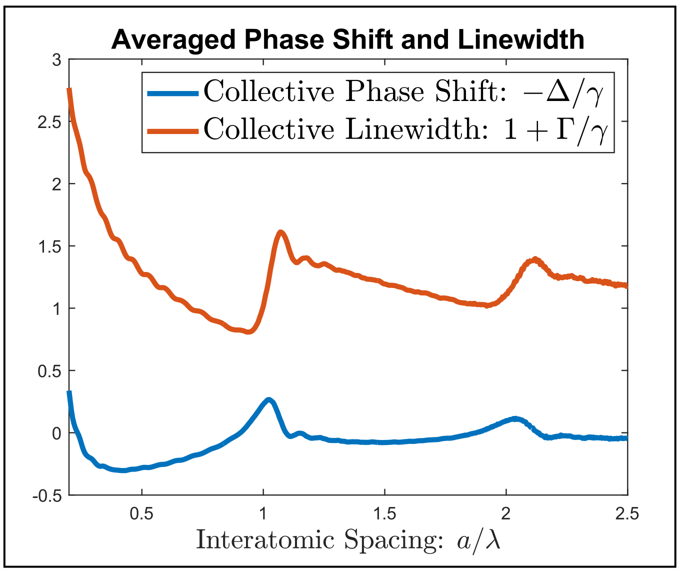

Fig. 2. Calculated dipole-enable phase shifts and damping for the ensemble in Figure 1. The interatomic spacing (a\λ) refers to the spacing of atoms along the spiral. Effects are averaged over the system to better match observed behavior, and values are normalized to the natural linewidth of the ions γ. The peaks of the damping correspond to specific dissipation channels, appearing as diffraction orders in the far field [3].

The lithium niobate substrate produces a non-uniform electric environment for the implanted ions due to the presence of defects in the material. The ions are subsequently inhomogeneously broadened, and many ions must be implanted at each site to ensure the presence of a single atom at the desired frequency. In this design we implant rows of approximately 2000 thulium ions for an average of one ion with unbroadened transitions per line. This broadening can also be employed for broadband operation of the device. Under this view, changes to the incident frequency of the light corresponds to a matching modification to the effective spacing of the ions due to a change in the wavelength of the in-plane wave.

IV. Conclusion

Based on these simulations, we believe that a spiral of atoms implanted in a solid-state host material exhibits notable properties for the manipulation of light. Such systems demonstrate the capability for directional scattering out of the plane of the array, with collective enhancements due to in-plane interactions. We have shown how the behavior of the ensemble is influenced by the dipole-dipole interactions between atoms and discussed how a solid-state host could accommodate such a design. Experiments to test the theoretical results presented are under way.

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