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Helical Bessel Beam Formation by an Archimedean Spiral Grating

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Abstract: A grating with a spiral shape is numerically proposed and experimentally analyzed to generate a 1st order Bessel beam. Numerical simulations show the characteristics of an acoustic vortex in the near field as the phase presents a screw dislocation and the field is null at the axis. The working frequency is f=2MHz and it is conceived for object manipulation.

Manipulation of objects without contact has many current applications like the control and management of a wide variety of particles[1]. Ultrasonic manipulation[2] of particles have been proven to be competitive with other techniques like holographic optical tweezers[3]. Handling large and heavy particles with acoustic fields is very appropriate since they provide greater radiation forces and momenta of magnitude than optical techniques. The acoustic radiation force is used to translate particles as a planar travelling wave carries a net linear momentum. Similarly, the acoustic radiation torque can change the angular orientation of an object as the tangential components give rise to orbital angular momentum[4]. An acoustic vortex beam is used for rotational manipulation by using acoustic fields. An acoustic vortex beam carries orbital angular momentum along the propagation direction that can be transferred to a particle.

One of the first attempts to generate an acoustic vortex consists on using a transducer surface that is physically offset by twisting like the coil of a spring[5]. This design has an important limitation: the transducer has a unique operating frequency of interest. This problem can be overcome by electronic means. In several works[6] a matrix array of transducers is used to generate a helical beam with an appropriate phase profile to rotate objects with ultrasound. In this way, the generated beam has an angular dependence. Signals emitted by each transducer are delayed in order to control the angular phase shift. In these active methods the discretization of the source is restricted by the number of transducers in the array. We propose here a passive system for the formation of acoustic vortex.

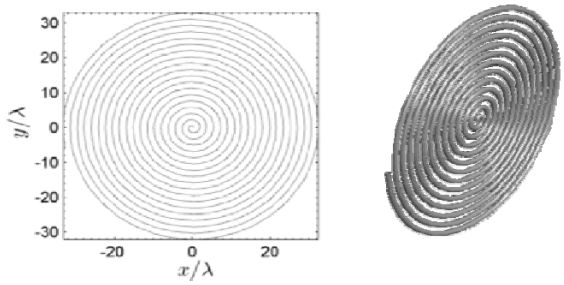


Figure 1 Scheme of the spiral grating with topological charge m=1. The profile corresponds to an Archimedean spiral defined in polar coordinates by equation $r(\theta)=b\cdot\theta$, where $b=1mm/2\pi$ is related to the distance between successive turnings.

A thin metallic layer (of width w=0.5mm) is used as a grating by perforating it with a particular shape to generate a helical beam. The grating is aligned and placed next to a flat ultrasonic transducer in such a way that the incoming wave is transformed into a helical wave. The wave transmitted through the grating is an acoustic vortex. The shape of the profile perforated in the grating is an Archimedean spiral as shown in Figure 1. Archimedean spirals are a family of spirals described in general by the equation

$$r(\theta)=b\cdot\theta+a \tag{1}$$

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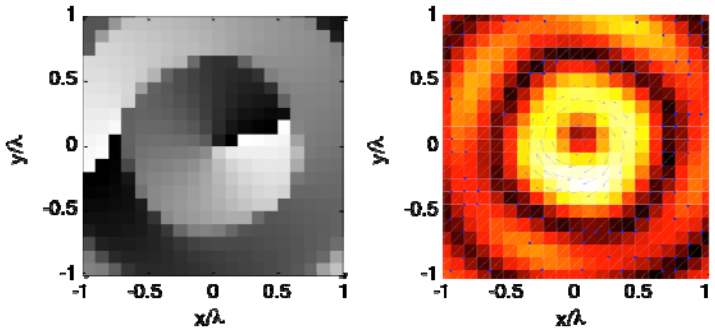


Figure 2. Numerical simulation of the helicoidal beam. a) Phase and b) magnitude of the transverse field of the acoustic vortex generated by the spiral lens working at frequency f=2MHz. The arrows represent the Intensity vector field. Spatial dimensions are normalized to the wavelength

The distance between two successive turnings is $b/2\pi$. Numerical simulations with Finite Difference in the Time Domain (FDTD) show that the field generated by the Archimedean spiral grating is an acoustic vortex. As the line defining the spiral (0.75mm) and the metallic layer (0.5mm) are very thin, the field generated by the grating is equivalent to a set of punctual sources. Figure 2 shows the phase (a) and the magnitude (b) of the vortex at distance z=10/λ. It can be seen a screw phase dislocation at the central axis of the spiral in (x=0,y=0) as a complete 2π phase shift in a turn around the propagation axes. For a finite number of turns of the spiral, the transversal profile of the acoustic field is represented by a 1st order Bessel function with the characteristic null amplitude null at the beam axis (remark the black spot at the center of Figure 2b). The arrows represent the intensity vector and show that the field carries angular momentum around the central axis. In Figure 3 the experimental measurements of the acoustic field are shown. Good agreement is found between numerical simulations and experimental results.

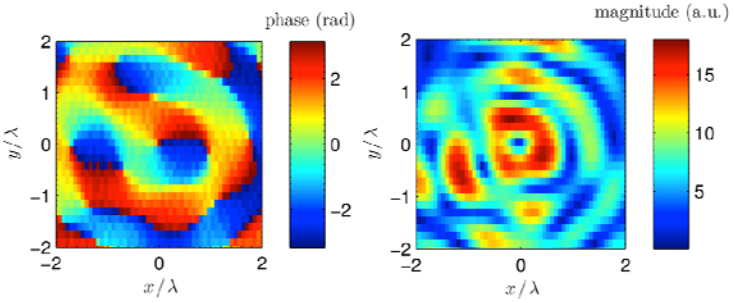


Figure 3. a) Phase and b) magnitude experimental measurements of the acoustic vortex generated by the Archimedean spiral grating at distance z=10/λ.

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