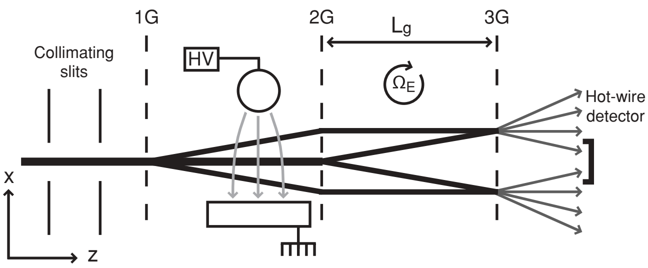

FIG. 1. Nanogratings 1G, 2G, and 3G form multiple Mach-Zehnder interferometers (two are shown). An atom passing through the interaction region acquires a phase ϕ_1, ϕ_0, and ϕ_{-1} along each path. The third grating acts as a mask for the 100-nm period interference fringes and also diffracts the interferometer output. The hot-wire detector is centered on the zeroth-order path. The distance between two gratings is $L_g = 940$ mm. The vertical (transverse) scale is exaggerated 10^4 times. The Earth rotation rate Ω_E modifies the measured phase shift.

in order to minimize systematic errors in measurements of polarizability ratios.

As in previous work [4–6], we place an interaction region between the first and second gratings to induce a differential phase shift in the interferometer. The phase shift is proportional to the atomic polarizability. Unlike references [4,5], we use an electric-field gradient region rather than a septum electrode as an interaction region. We use an electric-field gradient because the septum electrode would require fully separated diffraction orders and this is more difficult with heavier atoms such as potassium and rubidium.

The geometry of our interaction region is depicted in Fig. 2. The interaction region consists of a cylindrical electrode and a grounded plane. This geometry is the familiar "two-wire" configuration [12] rotated by 90° so that the height of the cylinder electrode is perpendicular, rather than parallel, to the beam paths. Our electrode orientation yields a relatively small fringe displacement (200 nm) compared to the standard electrode orientation for Stark deflections (200 μm) [3,13–17], but the sensitivity of atom interferometry allows us to make precise measurements of such small deflections. Two advantages of our electrode orientation are that the phase shift is homogeneous across the height of the atom beam and that there are no fringing fields entering and exiting the interaction region.

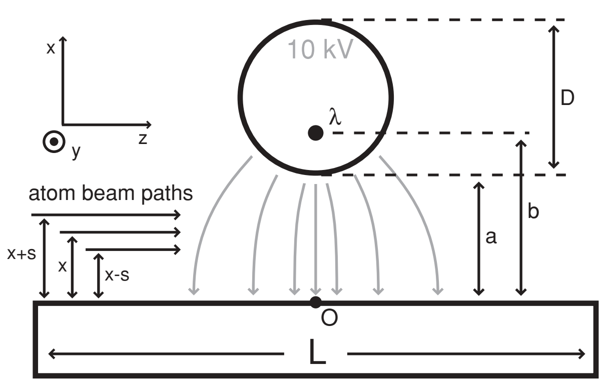

FIG. 2. Cross section of the interaction region (not to scale). The high-voltage electrode of diameter $D = 12.66$ mm is fixed at a distance $a = 1.998$ mm from the ground plane by precision spacers (not shown). The effective line charge λ is located a distance b from the ground plane, as discussed in the text. The ground plane is of length $L = 90$ mm. The high-voltage electrode and ground plane are 50-mm long in the y direction, while the beam height is only 1 mm. The zeroth order beam is a distance x from the ground plane and the ±first-order beams are a distance $x \pm s$ from the ground plane. Electric-field lines are shown in gray. The beam propagates along the z axis. O is the origin for the electric-field calculations.

We apply a voltage of 0–12 kV to the cylindrical electrode to create the electric-field gradient. Our electrode geometry is easily analyzed via the method of images [18]. The boundary conditions of our geometry, with cylindrical symmetry and an infinite ground plane, correspond exactly to the geometry in which an infinitely long line charge λ is fixed a distance b from the ground plane. The equipotential surfaces are circles of increasing radius centered at an increasing distance from the ground plane. We identify one of these equipotential surfaces as our electrode at a voltage V with radius R and located a distance a from the ground plane to determine the corresponding effective line charge λ and its position b:

$$\lambda = 2\pi\epsilon_0 V \ln^{-1}\left(\frac{a+R+b}{a+R-b}\right), \tag{2}$$

$$b = a\sqrt{1+2R/a}. \tag{3}$$

The resulting electric field is given by

$$\boldsymbol{E}_{(x,z)} = \frac{\lambda}{\pi\epsilon_0}\left\{\left[\frac{x-b}{(x-b)^2+z^2} - \frac{x+b}{(x+b)^2+z^2}\right]\hat{\boldsymbol{x}} + \left[\frac{z}{(x-b)^2+z^2} - \frac{z}{(x+b)^2+z^2}\right]\hat{\boldsymbol{z}}\right\}. \tag{4}$$

The potential energy of an atom in an electric field is given by the Stark shift $U_{\mathrm{Stark}} = -\frac{1}{2}\alpha E^2$. We use the WKB approximation to find the phase $\phi_\alpha(x,v)$ acquired by an atom along a path a distance x from the ground plane with velocity v and polarizability α:

$$\phi_\alpha(x,v) = \frac{\alpha}{2\hbar v}\int_{-\infty}^{\infty} E^2_{(x,z)}\,dz. \tag{5}$$

For our atom beam $U_{\mathrm{Stark}} \approx 10^{-7}$eV and $U_{\mathrm{kinetic}} \approx 0.1$eV, so the WKB approximation is valid. The integral of E^2 along the path of the atom may be performed using complex analysis and yields an acquired phase of

$$\phi_\alpha(x,v) = \frac{\lambda^2\alpha}{\pi\epsilon_0^2\hbar v}\left(\frac{b}{b^2-x^2}\right). \tag{6}$$

We induce a polarizability phase ϕ_α of up to 2500 rad along one path.

We will now discuss how the phase and contrast of the measured fringe pattern depends on the polarizability phase $\phi_\alpha(x,v)$. First, we define the phase difference between the paths of the two detected interferometers:

$$\begin{aligned}\phi_{\alpha,1}(x,v) &= \phi_\alpha(x+s,v) - \phi_\alpha(x,v),\\ \phi_{\alpha,-1}(x,v) &= \phi_\alpha(x,v) - \phi_\alpha(x-s,v).\end{aligned} \tag{7}$$

We studied phase differences $\phi_{\alpha,1}$ of up to 18 rad. Next, we perform an incoherent sum of the fringe patterns formed by atoms