Planar microwave structures for electron guiding

J Hoffrogge\textsuperscript{1} and P Hommelhoff\textsuperscript{1}

Max Planck Research Group \textquoteleft{}Ultrafast Quantum Optics\textquoteright{}, Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D85748 Garching, Germany
E-mail: johannes.hoffrogge@mpq.mpg.de and peter.hommelhoff@mpq.mpg.de

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Abstract. We present microwave electrode structures suited for guiding electrons propagating in a purely electric, alternating quadrupole field. In a first experiment using a standing wave on an electrically short structure, we previously demonstrated the general concept of electron confinement in microwave fields. Here, we discuss the extension to electrically long structures supporting travelling microwave excitations. This requires a modal decomposition of the voltage patterns on the multiconductor transmission line formed by the electrodes. We show that the use of a general five-wire structure leads to the distortion of the guiding potential upon propagation due to differing modal propagation constants. This can be avoided by implementing a coupled microstrip configuration with elevated signal electrodes. With structures like these, complex geometries connecting different beam manipulation elements can be realized, enabling new forms of electron experiments with guided matter waves.

\textsuperscript{1} Authors to whom any correspondence should be addressed.
1. Introduction

Electrons have played a key role in the demonstration of the wave nature of matter including diffraction [1] or interference [2, 3] experiments. For most of these experiments, freely propagating beams are used, which can be manipulated by conventional electron optical components [4]. Wholly new matter–wave systems could be realized if a propagating electron beam is guided in a transversally confining potential. This would constitute the matter–wave analogue of light guided in optical fibers allowing for the precise control of electron trajectories. Together with advanced guiding structures such as e.g. beamsplitters, multimode interference experiments might become feasible, similar to that proposed for neutral atoms in magnetic traps [5]. Furthermore, in combination with advanced electron sources that emit Heisenberg-limited electron beams [6], a direct population of the transverse ground state of a harmonic guiding potential should be feasible by electron-optical imaging. This would open the possibility of using the motional quantum state of the electrons as an experimental resource enabling, for example, direct two-state interference experiments of the ground- and first excited state of the guide, again in close analogy to existing proposals for trapped atoms [7, 8]. Also, the implementation of non-invasive electron microscopy schemes [9] or a coupling of guided electrons with other particles in near-by potentials, analogous to recent experiments with trapped ions [10, 11], might be feasible.

The dynamical confinement of charged particles in an alternating electric field, which is widely used in linear Paul traps [12, 13] for ions, is in principle also suited for electron guiding. However, the stable confinement of electrons in a purely electric field demands high driving frequencies in the microwave regime. This poses serious technical challenges when generating a suitable guiding field with macroscopic structures [14]. Furthermore, it inhibits shaping the potentials on small length scales and thus realizing complex guiding geometries. A technique that is better suited for this purpose, and is nowadays used with increasing frequency in ion trapping experiments, is based on surface-electrode configurations [15–20]. Here, the trapping potential is generated by microstructured planar electrodes in the ten to several hundred micrometer range [21]. For the operation at microwave driving frequencies, planar structures
have the additional advantage of being compatible with chip-based feeding lines, such as coplanar waveguides and microstrip lines [22, 23].

Recently, we demonstrated the guiding of low-energy electrons in free space above a chip-based electrode structure [24]. The guiding potential has been generated by a standing microwave excitation applied to electrodes with a longitudinal extension much smaller than the driving wavelength. To exploit the full potential of the technique and to realize, for example, beamsplitters for guided matter waves, it is desirable to implement longer structures that are not limited by the driving wavelength. In this case, the electromagnetic properties of the electrode structure at microwave frequencies become important and have to be considered in the guide design. To this end, we present in this paper a detailed microwave transmission line analysis of the five-electrode layout used in [24].

2. Surface-electrode electron guide

In an ideal linear quadrupole guide [12], charged particles are confined in an oscillating electric potential \( \Phi(r, t) = \Phi(r) \cdot \cos(\Omega t) \). This is generated by applying an alternating voltage with amplitude \( V \) and driving (circular) frequency \( \Omega \) to a set of four hyperbolically shaped electrodes at a distance \( R \) from the guide centre. The spatial part of the potential \( \Phi(r) = \Phi(x, z) \) is translationally invariant along the \( y \)-direction and has a quadrupolar shape in the transverse \( (x-z) \) plane. If the motion of the particle is slow compared to the driving frequency \( \Omega \), stable confinement is achieved. This can be quantified by a dimensionless stability parameter \( q = \frac{2Q}{m \cdot V/(\Omega^2 R^2)} \) with \( Q/m \) being the charge-to-mass ratio of the particle to be confined. Stable confinement is theoretically provided for \( q < 0.91 \), whereas typical devices are operated at \( q < 0.5 \). In this case, the motion of the particle can be approximated by that in a harmonic pseudopotential \( \Psi(r) = Q^2/(4m \Omega^2) \cdot |\nabla \Phi(r)|^2 \) with a small oscillating component at the driving frequency \( \Omega \) superimposed (conventionally termed micromotion) [13]. Independent of the sign of the particle’s charge, it experiences therefore a pseudopotential proportional to the square modulus of the electric field \( \mathbf{E}(r) = -\nabla \Phi(r) \). The guide centre forms at the electric field zero in the middle between the electrodes. The radial (circular) trapping frequency is given by \( \omega = q/\sqrt{8} \cdot \Omega \), while the potential depth is \( U = q/8 \cdot V \).

Analogous to surface-electrode ion traps [15], we generate this potential by applying the drive voltage to a structure of five electrodes fabricated on a planar substrate; see figure 1(a) for a cut in the transverse plane through the electrode structure. The pseudopotential minimum then forms at \( R = 500 \mu m \) above the central wire with the potential depth being limited by a saddle point above. Near the guide centre, the potential is approximately harmonic, albeit the transverse frequency is reduced by a factor of \( \eta = 0.31 \) compared to the ideal case. The reduction in potential depth due to the saddle point amounts to \( \mu = 0.0079 \). Note that the same factor \( \eta \) also has to be considered in the definition of the stability parameter \( q = \eta \cdot \frac{2Q}{m \cdot V/(\Omega^2 R^2)} \).

Due to the high charge-to-mass ratio of electrons, the operating parameters of an electron guide have to be quite different from the ion trapping case in order to achieve stable confinement at small \( q \). In the experiment reported on here, this has been done by increasing the driving frequency \( \Omega \) by a factor of nearly 100, as a decrease of \( V \) would simultaneously reduce the achievable potential depth \( U \), and the size of the structure is limited by fabrication considerations. For typical applied voltages of \( V = 30 \text{V} \) and guide-to-electrode distances of \( R \approx 500 \mu m \), a stability parameter of \( q \approx 0.3 \) can then be realized by a driving frequency in the microwave region of around 1 GHz. The corresponding pseudopotential \( \Psi(r) \) as depicted...
Figure 1. (a) Pseudopotential experienced by an electron above the planar guiding structure and (b) electric potential corresponding to the maximum voltage on the microwave electrodes. The microwave signal is applied to the red electrodes, whereas the blue structures are grounded and the substrate is shown in green. Electrode widths are \( c = 350 \mu m \) for the central one and \( w = 750 \mu m \) for the microwave electrodes; the outer ground planes extend to the edges of the substrate. The gaps between the electrodes are \( g = 110 \mu m \) wide and the wires are electroplated to a thickness of \( T = 40 \mu m \). The pseudopotential in (a) is calculated for a driving frequency of \( \Omega/(2\pi) = 1 \) GHz and a voltage amplitude of \( V = 30 \) V. Note that the pseudopotential (a) is stable in time, whereas the electrical potential (b) oscillates at the driving frequency.

One drawback that surface-electrode traps suffer from is increased motional heating presumably due to electric field noise above the electrode surface [25]. In comparison to ion traps, the higher transverse trapping frequencies achievable for electron guiding lead to a favourable scaling of the motional heating rates [24]. Comparing an ion trap at \( \omega/(2\pi) = 2.3 \) MHz trapping frequency having a measured heating rate of \( \dot{n} = 4800 \) quanta s\(^{-1} \) [17] to our electron guide with \( \omega/(2\pi) = 100 \) MHz, we expect a heating rate of only \( \dot{n} = 7 \) quanta s\(^{-1} \) for electron guiding. This should be sufficient for future interference experiments exploiting the transverse motional quantum state of guided electrons. It should therefore be possible to extend the already highly successful implementations of electron interference experiments with freely propagating electron beams [4] or electronic edge states in solid state systems [26] towards guided electron matter waves.

3. First-generation chip design

3.1. Chip design and microwave feeding

A top view of the complete electrode layout of the guiding structure used in a first demonstration experiment [24] is shown in figure 2(a). The substrate comprises two electrode planes fabricated.
Figure 2. (a) Sketch of the electrode layout as seen from above with voltage distributions along the electrodes, and (b) experimental signature of electron guiding. In panel (a), signal electrodes, where the microwave excitation is applied, are indicated in red, whereas the rest of the structure is grounded (blue). The bent guiding electrodes are fabricated on the top plane of the substrate and extend to the upper and lower edges of the substrate where the electrons enter and exit the guiding potential, respectively. The microwave excitation is fed from the right edge of the substrate by a coplanar transmission line on the bottom plane (indicated in purple), which runs perpendicular to the guiding electrodes and is connected to them by plated-through holes at the center of the substrate. The voltage amplitudes on the signal electrodes are indicated vertically along the guide and horizontally along the feeding line. In panel (b), we show an experimental signal of guided electrons, similar to the results presented in [24]. The exit of the guide is indicated by a circle, the substrate plane is located at the lower edge of the picture.

on its top and bottom sides. The guiding electrodes are placed on the top side and fully extend from the upper to the lower edge of the substrate. Electrons are injected into the guide at the upper edge, follow the curved path of the electrodes and are ejected at the lower edge. Successful guiding can thus be demonstrated by a deflection of the electron beam passing over the substrate. We feed the microwave signal by a coplanar transmission line on the bottom side of the substrate, which runs perpendicular to the guiding electrodes on the top side. It is connected to the guide by eight plated-through holes in the centre of the structure. As the
signal and ground electrodes of the guiding structure are not connected, the guide represents an approximately open-circuited termination of the transmission line. This leads to a standing microwave excitation on the guiding electrodes and the feeding lines with an antinode at the termination. The driving wavelength at $\Omega/(2\pi) = 1\,\text{GHz}$ amounts to $\lambda = 210\,\text{mm}$ (with the reduction due to the substrate taken into account), which is much larger than the longitudinal extension of the electrodes on the top plane $L/2 = 16\,\text{mm}$ (measured from the ends to the central feeding point). Therefore, the guiding electrodes can be considered as electrically short structures being at nearly equal potential over their entire length. To verify this, we have determined the voltage of the signal conductors with respect to the ground plane in a microwave probe station measurement. The result is sketched in figure 2(a) in a vertical coordinate system for the guiding electrodes and horizontally for the feeding line. The voltage is highest at the ends of the guiding structure with a voltage drop of about 5% towards the connection to the feeding line at the centre of the substrate. This leads to a small variation in the guiding parameters of as high 5% along the guide. On the feeding line, the voltage drops further until it reaches zero at a node of the standing wave forming at a distance of approximately $d = 15\,\text{mm}$ from the guide. As the connections of the two signal electrodes of the guiding structure are separated by a distance of 1.3 mm from each other, the voltage measured on the left electrode is approximately 10% higher than that measured on the right one. This voltage asymmetry leads to a shift of the guide centre by 34 $\mu\text{m}$ towards the right electrode without severely affecting the harmonicity of the potential minimum, as inferred from numerical simulations. In total, both effects are small enough to not inhibit guiding for the structure size implemented here.

3.2. Electron guiding

In figure 2(b), we show the experimental signature of electron guiding [24] obtained with the structure described in the previous section. A spot of guided electrons is visible at the exit of the guide indicated by a circle in the left part of the picture. The guide is operated at $\omega/(2\pi) = 101\,\text{MHz}$, $U = 22.5\,\text{meV}$ and $q = 0.27$. In the experiment, we used a thermal electron source with a collimated beam clipped by an aperture of 20 $\mu\text{m}$ diameter. For electrons with a kinetic energy of 4 eV, as employed here, a half-opening angle of 4$^\circ$ of the beam results in a transverse energy of $\approx 20\,\text{meV}$, which roughly equals the transverse potential depth. Some electrons are being lost during guiding and upon coupling to the guide, which is visible as a horizontal signal extending from the guide’s exit to the right. We expect the insufficient collimation of our source to be the main reason for that. Note also that the transverse potential additionally has to compensate for the centrifugal force on the electrons in the bent guide. From a current measurement at the detector, we deduce that on average less than one electron is in the guide at the same time. Space charge effects on the guided electrons are therefore negligible. For more details, see [24].

4. Multiconductor microwave transmission lines

For future experiments with advanced guiding structures, it is highly desirable to use longer guides. Operating these in a standing wave configuration would lead to even larger voltage differences distorting, and finally destroying, the guiding potential. An alternative is the implementation of a travelling microwave signal on the guiding electrodes with the electrons co- or counter-propagating above the wires. Here, the microwave signal is injected at one end.
of the structure, travels down the guide and is coupled out at the other end to avoid standing voltage waves. As the speed of low-energy electrons at several electronvolts is two orders of magnitude smaller than the velocity of the microwave signal \( v \approx c / \sqrt{\varepsilon_r} \), with \( \varepsilon_r \) being the relative permittivity of the surrounding material, the moving electrons still experience a (Doppler-shifted) oscillating transverse field, albeit now at a slightly reduced (or increased) frequency as compared to the stationary case. Thus the pseudopotential picture sketched in section 2 still holds.

As also mentioned in section 2, a quadrupole guide relies on a purely transverse electric field. Microwave transmission lines support propagating transverse electromagnetic (TEM) modes only in the ideal case of lossless conductors being surrounded by a homogeneous dielectric medium [27]. However, for inhomogeneous transmission lines with small losses and lateral dimensions and substrate thicknesses much smaller than the wavelength, the electromagnetic field around the conductors is mainly transverse with only a small longitudinal component. It can thus be approximated by a (quasi) TEM mode, which allows for the unique definition of a voltage and current excitation on the line.

4.1. Modal decomposition

For the simplest case of a uniform two-wire line and propagation in the \( y \)-direction, the voltage \( V(y, t) \) between the wires and the current \( I(y, t) \) running on one wire and returning on the other are given by [27]

\[
V(y, t) = V_0 \cdot \exp(-\gamma y + i \Omega t),
\]

\[
I(y, t) = I_0 \cdot \exp(-\gamma y + i \Omega t) = V_0 / Z_0 \cdot \exp(-\gamma y + i \Omega t).
\]

The characteristic impedance \( Z_0 \) connects the voltage and current amplitudes \( V_0 \) and \( I_0 \) travelling on the line, while the propagation constant \( \gamma = \alpha + i \beta \) is composed of the attenuation constant \( \alpha \) and the phase constant \( \beta \). Both \( Z_0 = [(R + i \Omega L) / (G + i \Omega C)]^{1/2} \) and \( \gamma = [(R + i \Omega L) \cdot (G + i \Omega C)]^{1/2} \) can be derived from a lumped circuit model with per-unit-length circuit elements \( C, L, R \) and \( G \); see figure 3(a). Here, \( C \) describes the capacity between the wires, \( L \) their mutual inductance, while \( R \) is the resistance of the wires and \( G \) the shunt conductance.
conductance due to dielectric loss in the surrounding medium. In the limit of small resistive and dielectric losses, the characteristic impedance and phase constant can be approximated by \( Z_0 = \sqrt{L/C} \) and \( \alpha = 0, \beta = \Omega \sqrt{L/C} \).

In the general case of a uniform transmission line in the \( y \)-direction consisting of \( N \) conductors, there are \( n = (N - 1) \) degrees of freedom for the voltage \( V_k(y, t) = V_k(y) \exp(i \Omega t) \), \( k = 1, \ldots, n \), of each single wire with respect to a reference conductor. Similarly, \( n \) independent currents \( I_k(y, t) = I_k(y) \exp(i \Omega t) \) can be defined propagating on each wire and returning on the reference electrode. These are connected by the transmission line equations [27]

\[
\frac{d}{dy} \begin{bmatrix} V_1(y) \\ \vdots \\ V_n(y) \end{bmatrix} = - \begin{bmatrix} Z_{11}(y) & \cdots & Z_{1n}(y) \\ \vdots & \ddots & \vdots \\ Z_{n1}(y) & \cdots & Z_{nn}(y) \end{bmatrix} \begin{bmatrix} I_1(y) \\ \vdots \\ I_n(y) \end{bmatrix},
\]

\[
\frac{d}{dy} \begin{bmatrix} I_1(y) \\ \vdots \\ I_n(y) \end{bmatrix} = - \begin{bmatrix} Y_{11}(y) & \cdots & Y_{1n}(y) \\ \vdots & \ddots & \vdots \\ Y_{n1}(y) & \cdots & Y_{nn}(y) \end{bmatrix} \begin{bmatrix} V_1(y) \\ \vdots \\ V_n(y) \end{bmatrix},
\]

with voltage and current vectors \( \mathbf{V}(y) = [V_1(y) \ldots V_n(y)] \) and \( \mathbf{I}(y) = [I_1(y) \ldots I_n(y)] \). The per-unit-length impedance and admittance matrices are defined by \( Z = R + i \Omega L \) and \( Y = G + i \Omega C \). The transmission line parameters \( C, L, R \) and \( G \) are now also matrices with coefficients being defined for each conductor pair. The differential equations (2) can be decoupled by a similarity transformation to modal coordinates, which leads to the modal solutions \( \mathbf{V}_{m,i}(y) = \mathbf{T}_i \exp(-\gamma_i y) \) and \( \mathbf{I}_{m,i}(y) = \mathbf{W}_i \exp(-\gamma_i y) \), with \( i = 1, \ldots, n \) and propagation constants \( \gamma_i = \alpha_i + i\beta_i \). The vectors \( \mathbf{T}_i = [T_{i,1}(y) \ldots T_{i,n}(y)] \) and \( \mathbf{W}_i = [W_{i,1}(y) \ldots W_{i,n}(y)] \) denote the voltage and current excitations of the \( i \)-th mode in the original, coupled basis. In total, each mode represents a specific set of conductor voltages \( \mathbf{T}_i \) and currents \( \mathbf{W}_i \), which travel with specific attenuation and phase constants \( \alpha_i \) and \( \beta_i \). The general solution for the voltages and currents on the line can now be written as \( \mathbf{V}(y) = \sum_{i=1}^{n} v_i \mathbf{T}_i \exp(-\gamma_i y) \) and \( \mathbf{I}(y) = \sum_{i=1}^{n} i_i \mathbf{W}_i \exp(-\gamma_i y) \) with the amplitudes \( v_i \) and \( i_i \) being determined by the initial conditions at the feeding point. Again, either the voltages or the currents on the line can be freely chosen as both are connected by a characteristic impedance matrix \( Z_0 \) that is defined by \( \mathbf{V}(y) = Z_0 \mathbf{I}(y) \).

As the \( \mathbf{T}_i \) and \( \mathbf{W}_i \) represent a complete set of \((N - 1)\) linearly independent vectors, every excitation of the line can be represented as a linear combination of the fundamental modes. Due to the, in general, different \( \alpha_i \) and \( \beta_i \), such a superposition will dephase while it propagates along the line so that the originally applied excitation will become increasingly distorted with increasing distance from the feeding point. As the guiding of electrons above a five-electrode structure relies on one specific voltage distribution on the wires (see figure 1(b)), which is not necessarily an eigenmode of the structure, a dephasing of the constituting modes will lead to an unwanted distortion of the harmonic pseudopotential and finally to the loss of the electrons.

### 4.2. Normal modes of the microwave guide

To further investigate this effect, we have computed the normal modes of the five-wire structure used in the present experiment [24]. As the two grounded outer electrodes are connected to
the ground plane on the bottom side of the substrate, the structure represents a four-conductor system. Taking the connected ground planes as the reference electrode, one obtains three degrees of freedom for the voltages on the central electrode and the two microwave electrodes; see figure 3(b). As the determination of the electromagnetic field of a (quasi-) TEM mode reduces to a static problem in the plane perpendicular to the propagation direction [22], a two-dimensional (2D) electrostatic field solver can be used to compute the distributed transmission line parameters [28]. Furthermore, in the case of small resistive and dielectric losses ($G \ll \Omega C$ and $R \ll \Omega L$), the voltages $T_i$ and the propagation constants $\gamma_i$ can be approximated by those of a lossless model with $R = 0$ and $G = 0$. We determined the capacitance matrix $C$ via a numerical simulation [29] of the 2D electrostatic field in the transverse plane [28]. Each element $C_{ij} = Q_j / V_i$ is computed by applying a voltage of 1 V to the $i$th conductor and determining the charge accumulating on the $j$th conductor. The inductance matrix $L$ can be derived in a similar fashion via $L = 1/c^2 \cdot C_0^{-1}$. Here, $c$ is the speed of light and $C_0$ the capacitance matrix computed with all dielectric media replaced by vacuum, which is done in a second electrostatic simulation.

In figure 4, we show the electric potential of the normal modes together with the directions of the electric field indicated by black arrows. In addition, the respective voltages of the individual conductors are given. The modes can be grouped into two symmetric and one antisymmetric mode with respect to the centre conductor. The first symmetric mode consists of a voltage vector of $T_1 = [0.535 \ 0.654 \ 0.535]$ V, where $T_{1,i}$ is the voltage on the left microwave conductor, $T_{1,2}$ that of the central conductor and $T_{1,3}$ that of the right microwave conductor. This mode propagates with a phase constant of $\beta_1 = 31.3 \text{ m}^{-1}$. The second one is characterized by $T_2 = [0.278 \ -0.919 \ 0.278]$ V and a phase constant of $\beta_2 = 29.9 \text{ m}^{-1}$.

It can be seen from figure 4 that the voltage configuration $V = [30 \ 0 \ 30]$ V used for electron guiding is not proportional to a normal mode of the structure but has to be composed as a linear combination of the two symmetric modes. The difference in phase constants of these modes leads to a relative dephasing, which accumulates to $\Delta = 7^\circ$ after a propagation length of $L = 10 \text{ cm}$. We performed a numerical particle tracking simulation in the time-dependent transverse electric field composed of two phase-shifted symmetric modes. We also included an unequal damping of the two modes due to their differing attenuation constants $\alpha_1 = 0.17 \text{ m}^{-1}$ and $\alpha_2 = 0.27 \text{ m}^{-1}$, which have been determined by a separate calculation including losses\textsuperscript{2}. The particle is released at the height of the pseudopotential minimum and 10 $\mu$m offset from the guide centre in the horizontal direction. The simulations show that the damping and dephasing of the two modes affect predominantly the vertical amplitude of the trajectory. For a phase shift of $\Delta = 7^\circ$, it increases to 200 $\mu$m compared with a negligible amplitude deviation at $\Delta = 0^\circ$. In addition, the pseudopotential picture no longer holds for such a distorted microwave field. Therefore, the currently used structure is not suited for future realizations of electrically long guides supporting a travelling microwave excitation and providing a harmonic pseudopotential with well-defined motional quantum states [30].

4.3. Electrically long guiding structures

One possible method of avoiding the distortion of the guiding potential is to use an electrode layout that supports the desired voltage configuration as a normal mode. This can

\textsuperscript{2} We used the 2D port mode routine of CST Microwave Studio; the phase constants agree within 1% with the results of the lossless quasi-TEM calculation.
Figure 4. Modal structure of a five-wire line. The colours represent the electric potential for the three normal modes supported by the structure. Additionally, the direction of the local electric field is indicated by black arrows and the voltages of the three inner electrodes are given. The two outer conductors are held at ground potential (0 V). The guiding field of figure 1 is generated by a superposition of the two symmetric modes (upper plots).

be accomplished, for example, by a coupled microstrip structure with elevated microwave conductors fabricated on insulating posts above a connected ground plane [23]; see figure 5. A similar structure has already been proposed [31] and demonstrated for ion trapping [32]. Although such a structure is slightly more complicated to fabricate due to the two metallization layers, it still offers the possibility of microscopic patterning that is needed for the realization of more complex guiding geometries. Because the number of free voltages is reduced to two here, the device supports only two normal modes; an even mode with both signal conductors at the same potential and an odd mode with the conductor voltages being equal in amplitude but opposite in sign. The even excitation can be used for electron guiding. It generates a pseudopotential minimum in the central plane between the conductors similar to the planar five-electrode case. For the dimensions shown in figure 5, the guide forms at a distance of 500 µm from the signal electrodes. The transverse frequency and potential depth achievable are slightly higher than those in the currently used configuration ($\eta = 0.39$, $u = 0.014$).

It is desirable to realize a sufficiently high characteristic impedance $Z_0 = V^2/2P$ because this increases the voltage amplitude $V$ on the conductors for a given microwave power $P$ applied. Therefore, the capacitance between the signal conductors and the ground plane should not be too high. On the other hand, the achievable potential depth increases for wider signal conductors. These requirements demand an elevation of the electrodes above the ground plane.
Figure 5. Pseudopotential of a coupled microstrip structure. The signal conductors (red) are fabricated on posts (shown in green) above a continuous ground plane (blue). The microwave electrodes are \( w = 570 \, \mu m \) wide with a spacing of \( g = 750 \, \mu m \) and a thickness of 20 \( \mu m \). The height of the insulating dielectric posts is \( H = 200 \, \mu m \). The pseudopotential has been calculated for a driving frequency of 1.02 GHz and a microwave amplitude of 30 V. The guiding parameters are \( \omega/(2\pi) = 144 \, \text{MHz} \), \( U = 53 \, \text{meV} \) and \( q = 0.4 \).

of the order of the electrode width \( w \). The silicon-on-insulator technology used in [32] only allows for elevations up to about 10 \( \mu m \) yielding characteristic impedances of several ohms for structure sizes in the 500 \( \mu m \) range. An alternative would be to use a high-aspect-ratio epoxy resin as the dielectric supporting the wires [33], which allows for much higher elevations and a resulting characteristic impedance of \( Z_0 = 50 \, \Omega \) for the dimensions shown in figure 5. Another option is to decrease the dimensions of the whole electrode structure to a guide-to-electrode distance of \( R_0 = 50 \, \mu m \). Here, sufficiently deep potentials can already be realized with an electrode width of several tens of \( \mu m \), leading to characteristic impedances of \( Z_0 = 50 \, \Omega \) for elevations compatible with silicon-on-insulator processes. These structures could then be fed directly by a conventional 50 \( \Omega \) transmission line without the need for impedance matching.

5. Summary

The demonstration of transverse confinement of propagating electrons in a linear quadrupole guide promises new experiments with guided matter waves. As the device is based on a microstructured planar electrode configuration, it can be easily extended to much more complex structures using conventional lithographic patterning techniques. For future experiments, it is especially desirable to realize electrically long structures with a longitudinal extension comparable to the driving wavelength. We have presented a detailed microwave transmission line analysis of the currently used device, showing that the voltage configuration needed for guiding is not a normal mode of the line. This leads to a distortion of the guiding potential while the excitation propagates on the line, rendering the current design unsuitable for the fabrication of long structures. We have therefore proposed and analysed an alternative electrode pattern based on coupled microstrips that supports the desired excitation as a normal mode and therefore avoids distortion. Depending on the scale of the electrode layout, this design could be
implemented with various existing fabrication methods. Besides the realization of long guiding structures, another important future step will be the demonstration of beam-splitting devices for guided electrons, similar to the $y$-junctions envisioned in ion trapping [21]. With these components at hand, completely new, chip-based electron matter-wave experiments will come within reach.

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