PAPER

Data transmission by quantum matter wave modulation

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Abstract
Classical communication schemes exploiting wave modulation are the basis of our information era. Quantum information techniques with photons enable future secure data transfer in the dawn of decoding quantum computers. Here we demonstrate that also matter waves can be applied for secure data transfer. Our technique allows the transmission of a message by a quantum modulation of coherent electrons in a biprism interferometer. The data is encoded in the superposition state by a Wien filter introducing a longitudinal shift between separated matter wave packets. The transmission receiver is a delay line detector performing a dynamic contrast analysis of the fringe pattern. Our method relies on the Aharonov–Bohm effect but does not shift the phase. It is demonstrated that an eavesdropping attack will terminate the data transfer by disturbing the quantum state and introducing decoherence. Furthermore, we discuss the security limitations of the scheme due to the multi-particle aspect and propose the implementation of a key distribution protocol that can prevent active eavesdropping.

Introduction

We are living in the information age, and almost every aspect of our modern society depends on secure data transfer. Classical communication schemes based on electromagnetic wave modulation are protected by complex mathematical encoding algorithms [1]. Their vulnerability to decoding by potential future quantum computers [2] with Shor’s algorithm [3] spurred the field of quantum cryptography and quantum information science with photons [4–7]. Exploiting the unique quantum behavior of photons led to further major achievements in quantum optics [8], e.g. the violation of Bell inequality [9], quantum teleportation [10] or quantum computing [11].

These photonic schemes are based on quantum uncertainty and entanglement. Another quantum cornerstone, the wave–particle duality, generated various matter wave experiments and applications for electrons [12], ions [13], atoms [14], molecules [15] and neutrons [16]. It was shown that almost any classical wave phenomenon has its counterpart realization with matter waves leading to particle interference [17] and Bragg scattering [18] of matter on light gratings, atomic Mach–Zehnder interferometer [19], transmission of electrons on bulk structures for tomography [20] or even an atom laser by releasing atoms from a Bose–Einstein condensate [21]. However, matter waves have yet not been exploited as carrier waves for the modulation and transmission of a signal, as it is common for classic electromagnetic data transfer.

In this paper, we describe such an approach, where a message is transmitted by a non-trivial quantum modulation of an electronic matter wave. We introduce and experimentally demonstrate a unique new data transfer scheme that is fundamentally different from the current quantum information science techniques with photons [22]. It can also not be realized classically or with neutral particle matter waves. Our method offers a valuable alternative to the future information market and can be suitable for situations where photons may not be the best choice. We discuss in detail that it provides a different kind of quantum security located between the classical and the quantum photonic schemes.

In our experiment, the matter waves of electrons in a biprism interferometer [12, 23–28] are used as the carrier waves to be modulated for signal transmission. The coherent electron beam is generated by a

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nanotip field emitter [29–31] and separated by a biprism fiber into two partial waves. After superposition by a quadrupole lens, an interference fringe pattern is formed on a delay line detector with a high spatial and temporal resolution [32]. Due to the limited energy width of the source, each detected electron has a slightly different wavelength. The ensemble of these matter waves can be described by a wave-packet with a distinct width being the longitudinal coherence length [33, 38]. With a Wien filter in the beam path the separated wave-packets can be longitudinally shifted toward each other decreasing the interference contrast [12, 33, 38, 39] without changing the classical electron pathways or the phase of the fringe pattern. The Wien filter modulation is based on the Aharonov–Bohm effect on charged particle waves [12] and therefore has no counterpart with photons or neutral atoms. The signal to be transmitted is encoded binary on the matter wave with the Wien filter by switching between high and low contrast. In this way, neither the beam position or the total intensity, nor the interference phase are changed revealing it as a truly quantum modulation dependent on the electrons wave nature. The data readout is realized by a dynamic contrast measurement. A transfer rate of 1 bit per 5 s was achieved with a secure transmission distance of 3.8 cm until the overlap of the separated beams. The signal transmission is demonstrated to be secure for decohering interceptions by introducing a semiconducting plate parallel to the electron beam paths. The Coulomb interaction between beam electrons and image charges in the semiconductor represents a passive eavesdropping attempt. It causes a transfer of which-path information which quenches the interference fringes due to decoherence [40], effectively annihilating the communication. We furthermore discuss the security limitations against active eavesdropping with a quantum device and siphoning part of the signal. To overcome such attacks, we propose a key distribution scheme for matter waves with similarities to the BB84 protocol for photons [5]. The required technical modifications for a future implementation in our current experimental setup are presented. It can reveal an active eavesdropping attack based on the quantum wave nature of the electrons. We also point out that our scheme has a lower security level due to its multi-particle aspect than the well-established single-photon cryptography protocols.

**Experimental setup**

The principles of electron biprism interferometry are explained in [12, 23]. Our setup and its application for communication by matter wave modulation are illustrated in figures 1(a) and (b). It includes several beam optic components from a former experiment by Sonnentag and Hasselbach [40]. A single atom nanotip field emitter [25, 29–31] is the origin of coherent electron waves. The beam is guided by electrostatic deflectors to illuminate the biprism. It consists of an Au/Pd-coated glass fiber with a diameter of 395 nm [25] and is placed between two grounded parallel plates. The fiber is set on a low negative potential between 0 and −1 V and can separate the beam coherently up to $\Delta x = 8.5 \mu m$. The partial waves are combined again by a quadrupole lens [35, 40]. Before they are superposed at the entrance of a quadrupole magnification lens, they pass a Wien filter [33] where the signal to be transmitted gets modulated on the electron waves as described below. The beam additionally traverses a magnetic coil as an image rotator to adjust the edges of the overlapping partial beams normal to the magnifying direction of the quadrupole. After superposition, the resulting fringe pattern is magnified by a factor of about 1500 and detected on a delay line detector with a high spatial and temporal single-particle resolution [32].

The non-zero energy width of the beam source $\Delta E$ and the quantum superposition principle allow describing the beam with wave-packets being the Fourier sum of individual linearly independent plane de Broglie waves of single electrons with slightly different energies [12, 33]. The Wien filter is used in classical physics as a velocity filter and energy analyzer for electron beams [36, 37]. In biprism electron interferometry the unit was rediscovered to correct for longitudinal wave-packet shifts [33]. They are introduced by electrostatic deflectors for beam alignment. The partial waves traverse in regions between the deflector plates with different electrostatic potentials. It leads to non-equal group velocities and different arrival times of the wave-packets on the detector. This in turn results in a longitudinally shifted overlap and a loss of contrast [12, 33, 38, 39]. When the shift is greater than the width of the wave-packets, defined as the longitudinal coherence length, then the fringe contrast vanishes. The Wien filter can compensate for this relative delay and reestablish maximum contrast [33]. It consists of an electrostatic deflector and two connected magnetic coils generating a magnetic and electric field both perpendicular to each other and the direction of the beam path (see figure 1(a)). The Wien filter is always used in a state where the effects of the electric and magnetic forces on the electrons cancel each other. In this so-called matched mode, the Wien filter does not deflect the beam or shift the phase of the interference pattern, it has therefore no classical influence on the electrons. However, the spatially separated partial wave-packets still experience different potentials between the Wien filter deflector plates which change their relative group velocities. The magnetic field does not introduce such an effect. For that reason, a combination of electric and magnetic fields can...
Figure 1. (a) Experimental setup for the data transmission by quantum matter wave modulation in an electron interferometer. The sender encodes the message on the matter wave with a Wien filter, the receiver decodes it on the detector. A possible eavesdropper intercepting between the Wien filter and the magnifying quadrupole would cause Coulomb decoherence [40] that shuts down the conversation. (b) Sketch of the Wien filter in the matched mode encoding a binary signal on the spatially separated matter wave packets by longitudinal shifts between large and small overlap. The corresponding high and low interference fringe contrast is read out dynamically in a delay line detector.

Figure 2. Dependency of the interference contrast with the Wien filter’s deflector voltage in the matched mode for two different beam path separations, $\Delta x = (2.9 \pm 0.4) \mu m$ (blue crosses) and $\Delta x = (3.8 \pm 0.4) \mu m$ (red circles). The data is fitted by Gaussian distributions (solid blue and chain dotted red line). Insets: the determined electron fringe pattern on the detector for low contrast state 1 (left, point A) and high contrast state 2 (right, point B) in the signal transmission process.

always be found to fully compensate for the original longitudinal shift of the other deflectors in the beamline. It restores maximal contrast [33] without beam deflection.

Results

In our new communication scheme, we use this mechanism to switch between two states in the Wien filter for binary signal transmission. The state 2 provides a full longitudinal overlap of the separated wave-packets on the detector and maximal contrast. For state 1, a voltage on the Wien filter deflector is applied (and the corresponding current through the magnetic coils for a matched state) to longitudinally shift the wave-packets toward each other slightly less than the coherence length. This results in a significantly reduced interference contrast. The two states and the dependency of the measured electron interference contrast as a function of the matched Wien filter deflector voltage are shown in figure 2 for two different beam path separations. The two insets indicate the interference pattern visible on the detector at those points (labeled as A and B in figure 2) which are switched for the binary encoding in the signal transmission. They reveal also the constant phase position of the fringe pattern.

With this setup, the first proof-of-principle experiment for information transfer by matter wave modulation was performed. The results are presented in figure 3. A user interface was coded where we input the message ‘matterwave modulation’. It was transmitted from the sender (Wien filter) to the receiver.
(detector) as indicated in figure 1. The program converts every letter in its binary representation and sends it to the control unit for the Wien filter. It consists of a pair of bipolar voltage sources for the Wien deflector, a bipolar current source for the Wien coils, and a microcontroller. For the binary number ‘1’, the deflector voltage and coil current were set to state 2 (point B), for the binary number ‘0’ they were set to state 1 (point A), as indicated in figure 2. At these two points, the corresponding high or low contrast fringe pattern were recorded. Each interferogram reveals a particle event integration over 1 s. This time binning is a balance between the count rate and the signal transmission rate. To avoid errors, enough counts are needed to make sure the contrast and phase can be determined. Thus, 4000 to 5000 counts/s were accumulated on the whole screen, resulting in 1000–1500 counts/s for each recorded interference pattern within five fringes. It is a sufficient signal to determine the fit parameters and the contrast with reasonable accuracy as described in the methods [27, 31]. The extracted interference contrast is plotted by the blue curve in figure 3. Five time bins are averaged to form one bit and the averaged values are represented by black rectangular bars. The message could thus be transmitted with a rate of 1 bit per 5 s. To determine if a bit is ‘0’ or ‘1’, a cut-off value was defined as (red line): $C_{\text{cutoff}} = 0.8 \times \bar{C}$, with $\bar{C}$ being the average contrast of all interferograms in the transmission. The readout software determines if an individual black bar value is above or below the red line and interprets it accordingly to a binary number ‘1’ or ‘0’. Every transmitted message is initialized by the bit sequence ‘000 010’ to normalize the length of a single bit before the start sequence is removed and the first sign begins. The end of the transmission is defined by the sequence ‘110 000’. After conversion into letters, the program reveals the correctly transmitted message, as presented by the binary numbers and corresponding letters above the data in figure 3. No incorrect bit was transferred.

Discussion

The biprism interferometer is comparable to the famous double-slit experiment in quantum physics [34]. It is well known that interference effects vanish as soon as the separated particle waves are measured before getting superposed [40–43]. For that simple reason, our transmission scheme intrinsically includes a high level of security beyond the classical scope against passive eavesdropping. The secure communication distance before superposition is between the Wien filter and the magnifying quadrupole. Since the coherent partial waves have not overlapped yet, direct measurement by an eavesdropper (denoted as (E) in the following) will only yield two independent beam spots of electrons and the modulated common information is lost. The exact distance depends on the number of fringes needed for analysis which is related to the width of the superposition, the superposition angle, the electron wavelength, and the resolution or magnification in the detection process. In this experiment, it is around 38 mm. Behind that point up to the detector, the partial waves are already superposed and the fringe pattern with the encoded information is visible at any place in different magnifications. This distance is 102 mm and cannot be considered to be secure. In the following, we discuss the security of our methods against passive and active eavesdropping. It leads to the conclusion that our quantum wave modulation technique has improved security compared to classical transmissions but also limitations compared to single-photon cryptography schemes due to the multi-particle character of the method.
Figure 4. The effect of an eavesdropper interfering with the communication. (a) A semiconducting doped silicon surface is introduced perpendicular to the biprism fiber direction at the lower image edge into the beam path before superposition. (b) Determined fringe pattern on the detector. The bright region indicates the surface. The proximity of such a conducting device decreases the interference contrast due to Coulomb-induced decoherence [40, 45–47]. (c) The fringe contrast is plotted versus the vertical distance between the surface and the electrons in the superposition state.

Eavesdropping with a classical device

Any attempt to ‘tap the line’ with a classical instrument would disturb the quantum superposition state and cause decoherence due to Coulomb-interaction [40, 45]. This reduces or destroys the interference contrast on which our binary coding technique is based on. In turn, the receiver would immediately detect the tapping attempt due to the loss of the transmitted signal. It is thereby not important if information about the electron waves is actually measured by an external observer or could only in principle be gained from the environment. For that reason, any conducting surface can represent the effect of an eavesdropper. The surface atoms (as being the environment) can resolve the which-path information of the electrons if the surface is close enough to the separated coherent beam paths. We studied and compared this Coulomb-induced decoherence with current theoretical models in detail elsewhere [45]. It was also experimentally analyzed in [40, 46] and theoretically discussed in [47–52]. The theoretical conclusions allow us to determine the contrast loss in a specific passive eavesdropping situation with a classical device and relate directly to the security arguments in our scheme. However, independent of the tapping device, the more information is gained the less contrast can be measured by the receiver which reveals the eavesdropper. Here, we demonstrate such an eavesdropping attempt by applying a one-cm-long doped silicon surface parallel and below the separated beamlines before superposition, as illustrated in figure 4(a).

The resulting fringe pattern on the detector from the aloof electron waves with a beam path separation of $\Delta x = 5.0 \mu m$ is shown in figure 4(b). Figure 4(c) plots the determined interference contrast as a function of the electron distance normal to the semiconducting surface. It can be clearly observed that the contrast drops from about 70% to zero within 5 $\mu m$. This represents the distinct effect of a passive eavesdropper who would be detected immediately and end the communication. The process depends on the beam path separation, surface conductivity and temperature [40, 45, 46]. As mentioned, our Wien filter scheme does not shift the fringe position on the detector and the electric and magnetic forces cancel each other. For that reason, nothing changes during switching between ‘0’ and ‘1’ for a classical measuring device and the separated electron pathways remain unaltered, making it impossible to gain any information about the transmitted signal. The only change in our electron beam is the group velocity of the wave-packets that classically alter the arrival times of the particles. However, since the electron emission is a Poisson distributed statistical process [25], the individual electron starting time is unknown, making the electron time differences not accessible. The security aspect of our scheme is therefore also a direct consequence of the random quantum tunneling process through the field emitters Coulomb barrier in the Schottky effect [53].
Figure 5. Schematic illustration of the interference contrast vs Wien filter deflector voltage from figure 2 to indicate the signal encoding points in the matter wave key distribution protocol. The shift between the separated wave-packets from max. to min. contrast is $\Delta$. The positions $0_{-}$, $0_{+}$, and $0_{++}$ indicate the points at multiples of $\Delta$ in both directions. An eavesdropper cannot distinguish between those 0-states, since in either case there is no contrast.

**Eavesdropping with a quantum device**

It is conceivable that the eavesdropper manages to coherently split all or part of the electron beam to reveal the transmitted signal. In this scenario, the interceptor deflects the separated coherent beams before overlap and superposes them on his own detector to measure the high and low contrast interference pattern according to the transmitted signal. For the case that the whole signal is captured, (E) could apply a second matter wave interferometer and induce a corresponding interference pattern into the optical axis of the receivers magnifying quadrupole and detector. With such a tapping setup, the receiver may not determine the presence of the eavesdropper. To reveal such an attack and accomplish secure data transfer, we present a new key distribution scheme using the quantum nature of the electron wave-packets. Our method has similarities to the BB84 protocol for quantum key distributions with photons [5]. It utilizes the symmetry of the curve in figure 2, where the contrast value at the indicated point C is equivalent to the one at point A. It leads to two possibilities of how a '0' can be encoded that an eavesdropper cannot distinguish. Let us assume for this scheme that points A and C in figure 2 are set further away from the center of the Gaussian curve such as illustrated by the points $0_{-}$ and $0_{+}$ in figure 5. They have the same zero contrast value within the error as any other point in the background far away from the wave-packets overlap. We also assume an equally negative and positive Wien filter shift $\Delta$ between minimal contrast at point $0_{-}$ or $0_{+}$ and the maximum contrast at perfect wave-packets overlap (point B in figure 2 or point 1 in figure 5). The positions where the partial wave-packets are shifted by $\pm 2\Delta$ from max. overlap are labeled as $0_{--}$ and $0_{++}$.

For our matter wave key distribution scheme, let us assume the implementation of a second Wien filter for signal encoding at the sender ($W_s$) and a further one at the receiver’s end ($W_r$), directly before the magnifying quadrupole. $W_s$ encodes the message by shifting the wave-packets by $\pm \Delta$ or leaving it as it is. The receiver’s $W_r$ randomly does the same ($\pm \Delta$ or no shift). After several turns, the sender and receiver exchange via a public channel for each bit how they have shifted (but not if they sent or measured a ‘0’ or a ‘1’). They only use those bits as an encryption key, where both did no shift, or where they did the opposite shift. This way, the receiver reverses the shift of the sender and measures the originally transmitted bit. For completeness, it is worth mentioning that in principle the first and second Wien filter of the sender can be combined to one Wien filter.

As a next step, the sender and receiver publicly exchange the remaining sent/received bits (or a separate small subset of the data) together with the applied shifts. Comparing the results are used to reveal a possible eavesdropper. To provide an example, if the sender sends a ‘1’ (max. contrast) and shifts it with $W_s$ by $-\Delta$ to a ‘0’ bit at point $0_{-}$ (see figure 5) and the receiver chooses to shift with $W_r$ also by $-\Delta$, he will end up at point $0_{--}$ and measure a ‘0’ bit (min. contrast). If an eavesdropper is in line and chooses ‘no shift’ in the Wien filter, he or she measures a ‘0’ not knowing if it was sent as a $0_{--}$, $0_{-}$, $0_{+}$ or $0_{++}$. In case he chooses to send it as a $0_{+}$, the receiver (after subtracting $\Delta$) will end up at the max. of the contrast curve at point ‘1’ and measure a ‘1’ bit. Since this is the opposite value as without the eavesdropper this interception can be revealed after the public data comparison. All possible settings on the sender and receiver site are summarized in table 1.

It also demonstrates the large uncertainty an eavesdropper has. If table 1 is considered a $3 \times 3$ matrix with the elements (row nr., column nr.) the three cases for the eavesdropper (E) can be analyzed in more detail:
Table 1. Possible combinations of wave-packet shifts from the sender and receiver for the matter wave key distribution protocol and the corresponding bit measurement. The columns are labeled by the points $0_-, 1$ or $0_+$ (see figure 5) where the sender sends the original bit ‘0’ or ‘1’ with the first Wien filter. The rows provide the possible shifts ($-\Delta$, ‘no’ (no shift) and $+\Delta$) for signal encoding with the sender’s second Wien Filter $W_s$. The first value in the boxes provides the signal state after the encoding by the sender ($0_-$ to $0_+$) and behind the arrow the receivers states after the decoding shifts by $W_r$ of $-\Delta$, ‘no’ and $+\Delta$.

| $0_-$ | 1 | $0_+$ |
|-------|---|-------|
| $-\Delta$ | $0_-$ | $-\Delta$ | 0_+ |
| $+\Delta$ | 0_+ | $+\Delta$ | 1 |
| $\text{no}$ | 0_+ | $\text{no}$ | 1 |
| $+\Delta$ | 1 | $+\Delta$ | 0_+ |
| $-\Delta$ | 0_+ | $-\Delta$ | 1 |
| $\text{no}$ | 1 | $\text{no}$ | 0_+ |
| $+\Delta$ | $0_+$ | $+\Delta$ | 0_+ |
| $-\Delta$ | $0_+$ | $-\Delta$ | 1 |
| $\text{no}$ | 1 | $\text{no}$ | 0_+ |
| $+\Delta$ | $0_+$ | $+\Delta$ | 0_+ |

Case 1, (E) has set his Wien filter on ‘no shift’ (no): (E) measures a 0: it could be (11), (12), (21), (23), (32), (33), (E) Measures a 1: it could be (13), (22), (31).

Case 2, (E) has set his Wien filter on $-\Delta$: (E) measures a 0: it could be (11), (12), (13), (21), (22), (23), (31), (33), (E) Measures a 1: it could be (23), (32).

Case 3, (E) has set his Wien filter on $+\Delta$: (E) measures a 0: it could be (11), (13), (22), (23), (31), (32), (33), (E) Measures a 1: it could be (12), (21).

For that reason, even in the best case when (E) measures a ‘1’, he or she has only a 50–50 chance to correctly forward the bit to the receiver. Without information about the applied shifts from the sender, the eavesdropper cannot decode the transmitted sequence. In case there is sufficient electron count rate for various contrast measurements (this important requirement will be discussed below), (E) could manage to capture all signal in an active attack and then coherently split the beam multiple times. This would allow (E) to connect several interferometers that are set on all possible wave-packet shifts ($-\Delta$, ‘no’, $+\Delta$). After the public exchange of the sender and receivers shift setting, (E) could decode the message. However, (E) still had to decide which state to forward to the receiver during transmission and will do this wrongly in several cases. For that reason, also in this case, our key distribution protocol would reveal the presence of the interceptor.

Besides capturing all signal, the eavesdropper could in principle split the beam coherently and siphon off unnoticed part of the electrons for interferometric analysis. There are three ways to prevent this scenario. One of them is to use a calibrated source where the count rate of the electrons is known by the sender and receiver beforehand. The second one is that the sender includes in his message the count rate he used during transmission. The third possibility was applied in figure 3 were we choose to keep the counts per fringe pattern low enough that only one party can measure the interference contrast. We accumulated 1000 to 1500 counts for each interferogram, which was just sufficient to determine the contrast without erroneous bits. In combination with the key distribution scheme, (E) would need to siphone enough signal to perform at least three additional contrast measurements, as described above. This is only possible if the accumulated counts per pattern are four times higher than in the case of the transmission of figure 3. Thus, our scheme becomes secure as soon as the time bin for a bit is chosen short enough with respect to the count rate. If the accumulated counts per fringe pattern are slightly above the minimal level to allow a contrast measurement without error, then (E) cannot siphone enough electrons to tap the line without annihilating the transmission. This security argument can even be extended if $W_s$ or $W_r$ shift by two or more $\Delta$, requiring additional beam splitting by (E) and more counts per fringe pattern. A general theoretical analysis of the security of our scheme is desired and a matter of future investigation. It may combine the noise in the setup, the stability of the source and the detection efficiency with the count rate, signal transfer rate and error bits in the transmission. This would allow determining the security level for various eavesdropping attempts and a comparison to quantum cryptography schemes with photons and classical encryption.

Comparison to single-photon cryptography

It is important to point out that our scheme includes a different kind of security compared to established quantum cryptography protocols with photons such as e.g. BB84 [5]. Quantum cryptography leverages the
uncertainty in the measurement of the single-photon quantum state that is protected by the no-cloning theorem [44]. The security of our scheme, on the other hand, depends on decoherence and the quantum nature (symmetry) of a matter wave packet. The message is encoded in the superposition and relies on the wave nature of each electron interfering with itself. However, to reveal the interference contrast, we need to sum over an ensemble of particles. This makes it a multi-particle scheme that is not protected by the no-cloning theorem. Additionally, the BB84 protocol transmits a fundamentally random sequence of ‘0’ and ‘1’-bits, which is the requirement for a perfectly secure key to encrypt messages. In our case, the sequence is chosen by the sender and influenced by the switching of the receiver. These major differences toward single-photon quantum cryptography lead to a lower security level of our transmission technique.

Future prospects and technical applications
We provide experimental evidence that a message can be securely encoded in the quantum superposition of electrons in an interferometer. Given the rise of quantum computers that possibly decode classical encryption schemes in the near future, our modulation scheme provides an alternative that is based on different quantum features than established single-photon cryptography methods. Our proof-of-principle experiment has yet a secure distance which is probably too short for direct technical applications. It certainly cannot compete with the established state-of-the-art photon quantum communication schemes. They allow secure intra-country distances accessible with glass fibers [54] or even over long, intercontinental distances via satellite communication [35]. However, the safe signal transmission distance in our scheme could be extended significantly by increasing the beam path separation. Coherent electron beam splitting up to 300 μm have been reported [56]. With the same superposition angle, secure transmission of 3.8 m is feasible with such a separation with state-of-the-art technology. It can be further extended to ~6 m by positioning the Wien filter closer to the tip, even between the tip and the biprism [33].

The implementation of the described key distribution scheme in our setup requires such technical modifications. In principle, only the second Wien filter just before the magnifying quadrupole needs to be added with the corresponding control electronics and software for the receiver part. However, due to limited space along our current beam path, adding this component requires prolonging the transmission distance which may only be realized with a larger beam path separation scheme [35].

Also, the data transfer rate has the potential to be improved significantly. We have been conservative with our signal rate, to preserve our source. However, driving our system to the maximum could increase the transmission rate by at least an order of magnitude. Optimizing the whole setup and the electron beam sources [25] could gain another factor 100. We experience a usual variation in the count rate of about 10%. This level of stability depends mainly on the source and can be improved by field emitter applied in electron microscopy and optimized for high stability [57]. Potential applications of our technique are short-range communication in environments, where photons cannot be applied due to an intensive light background on the sensors. It is also conceivable that in a low noise environment such as in space significantly larger beam paths separations and transmission distances are realistic. To improve signal quality and the influence of noise from the environment, it can be considered to include classical postprocessing. This would require to reverse an unwanted contrast loss introduced by dephasing or decoherence, both leading to erroneous bits. Dephasing by e.g. external frequencies [24, 26, 58] or vibrational noise [28] can be reversed by second-order correlation analysis with the tradeoff to require more counts per fringe pattern. Postprocessing is not possible in case of decoherence by e.g. Coulomb interaction [45] or by collisions with background gas molecules [42, 59], thereby the information-carrying contrast cannot be revealed.

The quest for novel quantum techniques for communication is important in various fields of modern science and technology. Here, we demonstrated in a proof-of-principle experiment that it is possible to perform a true quantum modulation on a matter wave for signal transfer in a biprism interferometer. The information is transmitted by a longitudinal wave-packet shift introduced by a Wien filter. We show that decoherence plays an important role in the security aspect and present a matter wave key distribution protocol to prevent an eavesdropping attack. It is also emphasized that the Wien filter has an electron-optical refractive index of one [12] and is able to shift the wave-packets longitudinally without shifting the transverse phase of the fringe pattern. This is a result of the compensating phase shifts from the magnetic and electric Aharonov–Bohm effects [12] for charged particles. For that reason, our scheme presents a unique method for electron waves. It is a separate class of information transfer technique based on matter wave quantum features and indicates a significant improvement in safety compared to classical communication.
Methods

We apply the Wien filter to shift the wave-packets of the separated beam paths as described in detail in [31, 33]. The Wien filter introduces a longitudinal shift of $\Delta r = \frac{l e U_{WF}}{D 2 U_{tip}}$, where $L$ is the length of the Wien filter deflector plates, $\pm U_{WF}$ the applied voltage, $D$ is the distance between them and $U_{tip}$ the electron acceleration voltage [31]. The longitudinal coherence length is the width of the wave-packets and can be calculated with $l_c = \frac{2 e U_{tip} \lambda}{e E}$, with $\lambda$ being the electron de Broglie wavelength at $U_{tip}$ [31].

The following parameters were applied for the signal transmission in figure 3: $L = 11.75 \, \text{mm}$, $\Delta x = (2.9 \pm 0.4) \, \mu\text{m}$ at a biprism voltage of $0.104 \, \text{V}$ and a combining quadrupole voltage of $-15.9 \, \text{V}$, $D = 8.75 \, \text{mm}$, $U_{tip} = -1000 \, \text{V}$, $\lambda = 38.8 \, \text{pm}$, $\Delta E = (377 \pm 40) \, \text{meV}$, $l_c = (66 \pm 7) \, \text{nm}$. The distances from the tip to the biprism, combining quadrupole (center), Wien filter (center) and magnifying quadrupole (center) have been $d_{tip-bp} = 83 \, \text{mm}$, $d_{tip-QP} = 125 \, \text{mm}$, $d_{tip-WF} = 237 \, \text{mm}$ and $d_{tip-QPmag} = 275 \, \text{mm}$, respectively.

For state 2 (high contrast) and state 1 (low contrast) the Wien filter deflector voltages were set. The wavepackets are shifted by $\Delta y = 58 \, \text{nm}$ at each state change. The corresponding currents in the Wien filter coil are set in a way that the beam deflection vanishes and the Wien filter is in the matched state. The whole setup is in an ultrahigh vacuum at a pressure of $1 \times 10^{-10} \, \text{mbar}$ and shielded by a mu-metal tube.

For every deflector voltage in the Wien curve of figure 2, five pictures with 250,000 particle events each were taken and averaged. Every single measurement lasts only approximately $1 \, \text{min}$ to avoid long-term drifts. The contrast value data points in figures 2 and 3 were determined by summing up the signal along the fringe direction to form a histogram. The fit function $I(x) = I_0 \cdot \left(1 + C \cdot \cos(\frac{2 \pi x}{d_s} + \phi_0)\right) \cdot \sin^2(\frac{\Delta x}{2 s_1} + \phi_1)$ was then applied as described in more detail elsewhere [27, 31]. Here, $C$ describes the interference contrast and $s$ the fringe distance. Further fitting parameters are the phases $\phi_0, \phi_1$, the average intensity $I_0$ and the width of the interference pattern $s_1$.

For the contrast analysis in figure 4(c), the interference was determined as a function of the surface distance. Each contrast point is evaluated by slicing a horizontal rectangular section of the image normal to the fringe orientation with a height of 400 nm. The counts in each slice were summed up to form a histogram that was fitted with the above function. The contrast was normalized to the undisturbed value at distances higher than $20 \, \mu\text{m}$ to the semiconducting surface.

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Data availability statement

All data that support the findings of this study are included within the article.

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